BIBLIOGRAPHY

PIEZOELECTRICITY

Certain materials produce electrical charges on their surfaces as a consequence of applied mechanical stress. The induced charges are proportional to the mechanical stress. This is called the direct piezoelectric effect and was discovered by Jacques and Pierre Curie in 1880. Materials showing this phenomenon also conversely have a geometric strain proportional to an applied electric field. This is the converse piezoelectric effect. The root of the word "piezo" means "pressure"; hence the original meaning of the word piezoelectricity implied "pressure electricity" (1,2).

Piezoelectric materials provide coupling between electrical and mechanical parameters. The material used earliest for its piezoelectric properties was single-crystal quartz. Quartz crystal resonators for frequency control appear today at the heart of clocks and are also used in TVs and computers. Ferroelectric polycrystalline ceramics such as barium titanate and lead zirconate titanate exhibit piezoelectricity when electrically poled. Since these ceramics possess significant and stable piezoelectric effects, that is, high electromechanical coupling, they are capable of producing large strains/forces and hence are extensively used as transducers. Piezoelectric polymers, notably polyvinyliden difluoride and its copolymers with trifluoroethylene and piezoelectric composites combining a piezoelectric ceramic with a passive polymer, have been developed which offer a high potential. Recently, thin films of piezoelectric materials are receiving attention due to their potential utilization in microsensors, microtransducers, and microactuators.

Piezoelectricity is being extensively utilized in the fabrication of various devices such as transducers, actuators, surface acoustic wave devices, frequency control, and so on. In this article we discuss the piezoelectric effect, a brief history of piezoelectricity followed by present-day piezoelectric materials that are used, and finally various potential applications of piezoelectric materials.

PIEZOELECTRICITY

Relationship Between Crystal Symmetry and Properties

All crystals can be classified into 32 point groups according to their crystallographic symmetry. These point groups are divided into two classes; one has a center of symmetry and another lacks it. There are 21 noncentrosymmetric point groups. Crystals belonging to 20 of these point groups exhibit piezoelectricity. The cubic class 432, although lacking a center of symmetry, does not permit piezoelectricity. Of these 20 point groups, there are 10 polar crystal classes containing a unique axis, along which an electric dipole moment is oriented in the unstrained condition.

Pyroelectric effect appears in any material that possesses a polar symmetry axis. As a result of this the material develops an electrical charge on the surface owing to change in magnitude of the dipole moment with changing temperature. Among the pyroelectric crystals whose spontaneous polarization are reorientable by application of an electrical field of sufficient magnitude (not exceeding the breakdown limit of the crystal) are ferroelectrics (3,4). Table 1 shows the crystallographic classification of the point groups.

Piezoelectric Coefficients

Materials are deformed by stresses and the resulting deformations are represented by strains ($\Delta L/L$). When the stress $\boldsymbol{T}$ (force per unit area) causes a proportional strain $\boldsymbol{S}$,

$$\boldsymbol{S} = \boldsymbol{sT} \tag{1}$$

where all quantities are tensors; $\boldsymbol{S}$ and $\boldsymbol{T}$ are second rank and $\boldsymbol{s}$ is fourth rank. Piezoelectricity creates additional strains by applied field $\boldsymbol{E}$. The piezoelectric equation is given by

$$\boldsymbol{S}_{ij} = \boldsymbol{s}_{ijkl}\boldsymbol{T}_{kl} + \boldsymbol{d}_{ijk}\boldsymbol{E}_k \tag{2}$$

where $\boldsymbol{E}$ is the electric field and $\boldsymbol{d}$ is the piezoelectric constant which is the third rank tensor. This equation can be also expressed in a matrix form such as given for the case in a poled ceramics:

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} & & & 0 \\ s_{12} & s_{11} & s_{13} & & & \\ s_{13} & s_{13} & s_{33} & & & \\ & & & s_{44} & & \\ & 0 & & & s_{44} & \\ & & & & & 2(s_{11}-s_{12}) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{31} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \tag{3}$$

Another frequently used piezoelectric constant is g which gives the electric field produced when a stress is applied ($\boldsymbol{E} = \boldsymbol{gT}$). The $\boldsymbol{g}$ constant is related to the $\boldsymbol{d}$ constant through the permittivity $\boldsymbol{\epsilon}$:

$$\boldsymbol{g} = \boldsymbol{d}/\boldsymbol{\epsilon} \tag{4}$$

A measure of the effectiveness of the electromechanical energy conversion is the electromechanical coupling factor $\boldsymbol{k}$ which measures the fraction of the electrical energy converted to mechanical energy when an electric field is applied or vice versa when a material is stressed (5). The relationship is in

Table 1. Crystallographic Classification in Terms of Polarity and Centrosymmetry

Polarity	Symmetry	Crystal System: Cubic		Hexagonal		Tetragonal		Rhombohedral		Orthorhombic	Monoclinic	Triclinic
Non-polar [22]	Centro [11]	m3m	m3	6/mmm	6/m	4/mmm	4/m	$\bar{3}$m	$\bar{3}$	mmm	2/m	
	Non-centro [21]	432 $\bar{4}$3m	23	622 $\bar{6}$m2	$\bar{6}$	422 $\bar{4}$2m	$\bar{4}$	32		222		
Polar (Pyroelectric) [10]				6mm	6	4mm	4	3m	3	mm2	2 m	1

Inside the bold line are piezoelectrics.

terms of $\boldsymbol{k}^2$.

$$\boldsymbol{k}^2 = \frac{\text{Electrical energy converted to mechanical energy}}{\text{Input electrical energy}} \tag{5}$$

or

$$\boldsymbol{k}^2 = \frac{\text{Mechanical energy converted to electrical energy}}{\text{Input mechanical energy}} \tag{6}$$

which also can be expressed by

$$\boldsymbol{k}^2 = \boldsymbol{d}^2/(\epsilon \cdot \boldsymbol{s}) \tag{7}$$

$\boldsymbol{k}$ is always less than 1, because $\boldsymbol{k}^2$ is below 1. Typical values of k are 0.10 for quartz, 0.4 for $BaTiO_3$ ceramic, 0.5 to 0.7 for PZT (lead zirconate-titanate) ceramic and 0.1 to 0.3 for PVDF (polyvinylidene difluoride) polymer. Another important material parameter is the mechanical quality factor Q_m which determines the frequency characteristics. The Q_m is given by

$$Q_m = 2\pi \times \frac{\text{Energy stored over one cycle}}{\text{Energy dissipated per cycle}} \tag{8}$$

HISTORY OF PIEZOELECTRICITY

As stated already the discovery of piezoelectricity in quartz (which is not ferroelectric) was done by Pierre and Jacques Curie in 1880. Ferroelectricity can provide the creation of useful piezoelectric materials. Rochelle salt was the first ferroelectric discovered in 1921. Until 1940 only two types of ferroelectrics were known, Rochelle salt and potassium dihydrogen phosphate and its isomorph. From 1940 to 1943, unusual dielectric properties such as the abnormally high dielectric constant of barium titanate $BaTiO_3$ were discovered independently by Wainer and Salmon, Ogawa, and Wul and Golman. After the discovery, compositional modifications for $BaTiO_3$ led to improvement in the temperature stability or the high voltage output. Piezoelectric transducers based on $BaTiO_3$ ceramics were becoming well established in a number of device applications.

In the 1950s Jaffe and co-workers established the lead zirconate–lead titanate system (called PZT system) as suitable for inducing strong piezoelectric effects. The maximum piezoelectric response was found for PZT compositions near the morphotropic phase boundary, that is, the composition-dependent and temperature independent rhombohedral-tetragonal phase change. Since then, the PZT system with various additives has become the dominant piezoelectric ceramics for potential applications. Other ferroelectric perovskite compounds were also extensively examined. The discovery of PZT solid solution systems was rapidly followed by its exploitation in a number of practical piezoelectric applications.

Kawai et al. discovered in 1969 that certain polymers, notably polyvinyliden difluoride, are piezoelectric when stretched during fabrication. Such piezoelectric polymers are also useful for some transducer applications. In 1978 Newnham et al. improved composite piezoelectric materials by combining a piezoelectric ceramic with a passive polymer whose properties can be tailored to the requirements of various piezoelectric devices.

There is another class of ceramic material which recently has become important; relaxor-type electrostrictors such as lead magnesium niobate (PMN), typically doped with 10% lead titanate (PT), which are potentially used for applications in piezoelectric actuator field. Recent breakthrough in the growth of high quality large single crystal relaxor piezoelectric compositions has brought the interest in these materials for wide applications ranging from high strain actuators to high frequency transducers for the medical ultrasound devices due to their superior electromechanical characteristics. More recently, thin films of piezoelectric materials such as zinc oxide (ZnO), or PZT have been extensively investigated and developed for use in microelectromechanical device applications.

PIEZOELECTRIC MATERIALS

This section summarizes the current status of piezoelectric materials: single crystal materials, piezoceramics, piezopolymers, piezocomposites, and piezofilms. Table 2 shows the material parameters of some representative piezoelectric materials described next (6,7).

Single Crystals

More recently, the piezoelectric ceramics are widely used for a large number of applications. However, single crystal materials retain their utility, being essential for application fields such as frequency stabilized oscillators and surface acoustic

Table 2. Properties of Piezoelectric Materials

Parameter	Quartz	$BaTiO_3$	PZT 4	PZT 5H	$(Pb,Sm)TiO_3$	PVDF-TrFE
d_{33} (pC/N)	2.3	190	289	593	65	33
g_{33} (10^{-3}Vm/N)	57.8	12.6	26.1	19.7	42	380
k_t	0.09	0.38	0.51	0.50	0.50	0.30
k_p		0.33	0.58	0.65	0.03	
$\epsilon_{33}{}^T/\epsilon_0$	5	1700	1300	3400	175	6
Q_m	$>10^5$		500	65	900	3–10
T_c(°C)		120	328	193	355	

devices. The most popular single-crystal piezoelectric materials are quartz, lithium niobate ($LiNbO_3$) and lithium tantalate ($LiTaO_3$). The single crystals are anisotropic, which gives different material properties depending on the cut of the materials and the direction of bulk or surface wave propagation.

Quartz is a well-known piezoelectric material. α-quartz belongs to triclinic crystal system with point group 32 and has a phase transition at 537°C to β-type which is not a piezoelectric. Quartz has the cut with a zero temperature coefficient. For instance, quartz oscillators using a thickness shear mode of AT-cut are extensively used for clock sources in computers, and frequency stabilized ones in TVs and VCRs (videocasette recorders). On the other hand, an ST-cut quartz substrate with X-propagation has a zero temperature coefficient for surface acoustic waves (SAWs) and so are used for SAW devices with high-stabilized frequencies. The other distinguishing characteristic of quartz is that it has an extremely high mechanical quality factor $Q_m > 10^5$.

Lithium niobate and lithium tantalate belong to an isomorphous crystal system and are composed of oxygen octahedron. The Curie temperatures of $LiNbO_3$ and $LiTaO_3$ are 1210 and 660°C, respectively. The crystal symmetry of the ferroelectric phase of these single crystals is 3 m and the polarization direction is along the c-axis. These materials have high electromechanical coupling coefficients for surface acoustic waves. In addition, large single crystals can easily be obtained from their melt using the conventional Czochralski technique. Thus, both materials occupy very important positions in the surface acoustic wave device application field.

Ceramics

Perovskite Structure. Most of the piezoelectric ceramics have perovskite structure ABO_3, as shown in Fig. 1. This ideal structure consists of a simple cubic unit cell with a large cation A on the corner, a smaller cation B in the body center, and oxygen O in the centers of the faces. The structure is a network of corner-linked oxygen octahedra surrounding B cations. Piezoelectric properties of perovskite-structure materials can be easily tailored depending on their applications by incorporating various cations in the perovskite structure.

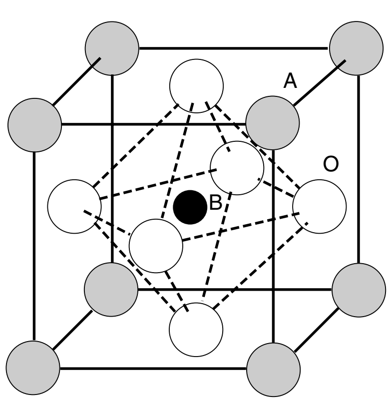

Figure 1. Perovskite structure ABO_3. This ideal structure consists of a simple cubic unit cell with a large cation A on the corner, a smaller cation B in the body center, and oxygen O in the centers of the faces.

Barium Titanate. Barium titanate ($BaTiO_3$) is one of the most thoroughly studied and most widely used piezoelectric materials. Figure 2 shows the temperature dependence of dielectric constants in $BaTiO_3$ demonstrating the phase transition in $BaTiO_3$ single crystals. Three anomalies can be observed. The discontinuity at the Curie point (130°C) is due to a transition from a ferroelectric to a paraelectric phase. The other two discontinuities are accompanied with transitions from one ferroelectric phase to another. Above the Curie point the crystal structure is cubic and has no spontaneous dipole moments. At the Curie point the crystal becomes polar and the structure changes from a cubic to a tetragonal phase. The tetragonal axis is in the direction of the dipole moment and thus along the spontaneous polarization. Just below the Curie temperature, the vector of the spontaneous polarization points in the [001] direction (tetragonal phase), below 5°C it reorients in the [011] (orthrhombic phase) and below −90°C in the [111] (rhombohedral phase). The dielectric and piezoelectric properties of ferroelectric ceramic $BaTiO_3$ can be affected by its own stoichiometry, microstructure, and by dopants entering into the A or B site solid solution. Modified ceramic $BaTiO_3$ with dopants such as Pb or Ca ions have been used as commercial piezoelectric materials.

Lead Zirconate–Lead Titanate. Piezoelectric $Pb(Zr,Ti)O_3$ solid solutions (PZT) ceramics have been widely used because of their superior piezoelectric properties. The phase diagram of the PZT system ($PbZr_xTi_{1-x}O_3$) is shown in Fig. 3. The crystalline symmetry of this solid-solution system is determined by the Zr content. Lead titanate also has a tetragonal ferroelectric phase of perovskite structure. With increasing Zr content, x, tetragonal distortion decreases and when $x > 0.52$ the structure changes from tetragonal 4 mm phase to another ferroelectric phase of rhombohedral 3 m symmetry. This transition is rather independent of temperature. The line dividing the two phases is called morphotropic phase boundary, that is, the change of symmetry occurs only as a function of composition. This composition is considered to have both phases. Figure 4 shows the dependence of several $\boldsymbol{d}$ constants on composition near the morphotropic phase boundary. The $\boldsymbol{d}$ constants have their highest values near the morphotropic phase boundary. This enhancement in piezoelectric effect is attributed to the increased ease of reorientation of the polarization

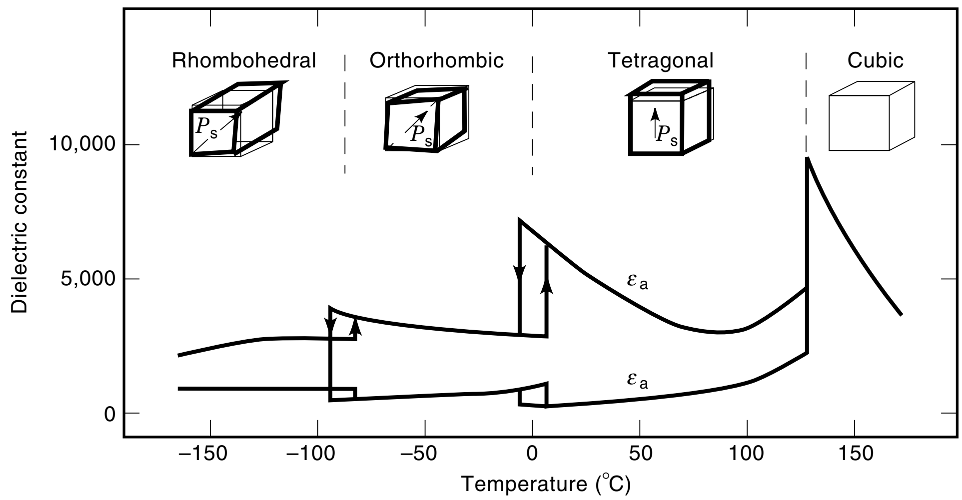

Figure 2. Dielectric constants of $BaTiO_3$ as a function of temperature. Three anomalies accompanied with phase transitions can be observed.

under electric field. Doping the PZT material with donors or acceptors changes the properties dramatically. Donor doping with ions such as Nb^{5+} or Ta^{5+} provides soft PZTs like PZT-5, because of the facility of a domain motion due to the resulting Pb-vacancy. On the other hand, acceptor doping such as Fe^{3+} or Sc^{3+} leads to hard PZTs such as PZT-8, because oxygen vacancies will pin the domain wall motion.

Lead Titanate. Lead titanate has a large crystal distortion. $PbTiO_3$ has tetragonal structure at room temperature with its tetragonality approximately equal to 1.063. The Curie temperature is 490°C. Densely sintered $PbTiO_3$ ceramics cannot be obtained easily, because they break up into a powder when cooled through the Curie temperature. This is due to the large spontaneous strain which occurs at the transition. Lead titanate ceramics modified by adding small amounts of additives exhibit a high piezoelectric anisotropy. Either (Pb, Sm)TiO_3 (8) or (Pb, Ca)TiO_3 (9) has extremely low planar coupling, that is, large k_t/k_p ratio. Here, k_t and k_p are thickness-extensional and planar electromechanical coupling factors, respectively. (Pb, Nd)(Ti, Mn, In)O_3 ceramics with a zero temperature coefficient of surface acoustic wave delay have been developed as a superior substrate materials for SAW device applications (10).

Polymers

Polyvinylidene difluoride, PVDF or PVF2, is piezoelectric when stretched during fabrication. Thin sheets of the cast polymer are then drawn, stretched, in the plane of the sheet in at least one direction, and frequently also in the perpendicular direction, to make the material into its microscopically polar phase. Crystallization from melt forms nonpolar α-phase, which can be converted into another polar β-phase by a uniaxial or biaxial drawing operation; these dipoles are then reoriented through electric poling. Large sheets can be manufactured and thermally formed into complex shapes. The copolymerization of vinilydene difluoride with trifluoroethylene

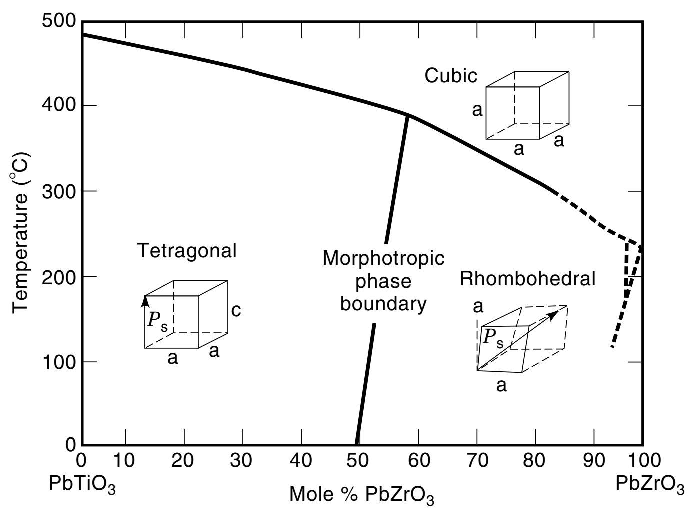

Figure 3. Phase diagram of the PZT system. The crystalline symmetry of this solid-solution system is determined by the Zr content. The line dividing the two, tetragonal and rhombohedral phases is called morphotropic phase boundary.

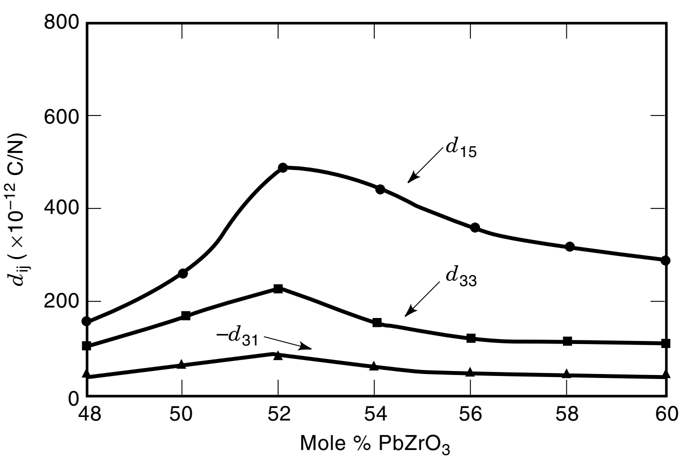

Figure 4. Several piezoelectric d strain coefficients versus composition near the morphotropic phase boundary for the PZT system. The d coefficients have their highest values near the morphotropic phase boundary.

(TrFE) results in random copolymer (PVDF-TrFE) with a stable, polar β-phase. This polymer need not be stretched; it can be poled directly as formed. The thickness-mode coupling coefficient of 0.30 has been reported. Such piezoelectric polymers are used for directional microphones and ultrasonic hydrophones.

Composites

Piezocomposites composed of a piezoelectric ceramic and polymer are promising materials because of excellent and tailored properties. The geometry for two-phase composites can be classified according to the connectivity of each phase (1, 2, or 3 dimensionally) into 10 structures; 0-0, 0-1, 0-2, 0-3, 1-1, 1-2, 1-3, 2-2, 2-3 and 3-3 (11). A 1-3 piezocomposite, or PZT–rod/polymer–matrix composite, is identified as a most promising candidate. The advantages of this composite are high coupling factors, low acoustic impedance, good matching to water or human tissue, mechanical flexibility, broad bandwidth in combination with low mechanical quality factor, and the possibility of making undiced arrays by only structuring the electrodes. The thickness-mode electromechanical coupling of the composite can exceed the k_t (0.40 to 0.50) of the constituent ceramic, almost approaching the value of the rod-mode electromechanical coupling, k_{33} (0.70 to 0.80) of that ceramic (12). Acoustic impedance is the square root of the product of its density and elastic stiffness. The acoustic match to tissue or water (1.5 Mrayls or $kgm^{-2}s^{-1}$) of the typical piezoceramics (20 to 30 Mrayls) is significantly improved by forming a composite structure, that is, by replacing heavy and stiff ceramic by light and soft polymer. Piezoelectric composite materials are especially useful for underwater sonar and medical diagnostic ultrasonic transducer applications.

Thin-Films

Both zinc oxide (ZnO) and aluminum nitride (AlN) are simple binary compounds with a Wurtzite-type structure, which can be sputter-deposited in a c-axis oriented thin film on a variety of substrates. ZnO has large piezoelectric coupling and its thin films are widely used in bulk acoustic and surface acoustic wave devices. The fabrication of highly c-axis oriented ZnO films has been extensively studied and developed. The performance of ZnO devices is, however, limited due to their small piezoelectric coupling (20 to 30%). PZT thin films are expected to exhibit higher piezoelectric properties. At present, the growth of PZT thin film is being carried out for use in microtransducers and microactuators.

Relaxor-Type Ferroelectric Materials

Relaxor ferroelectrics differ from normal ferroelectrics in terms of having broad phase transition from paraelectric to ferroelectric state, strong frequency dependence of dielectric constant (i.e., dielectric relaxation) and weak remanent polarization. Lead based relaxor materials have complex disordered perovskite structures with a general formula $Pb(B_1, B_2)O_3$ ($B_1 = Mg^{2+}, Zn^{2+}, Sc^{3+}$, $B_2 = Nb^{5+}, Ta^{5+}, W^{6+}$). The B site cations are distributed randomly in the crystal. The characteristic of relaxors is a broad and frequency dispersive dielectric maximum. Relaxor-type electrostrictive materials such as lead magnesium niobate $Pb(Mg_{1/3}Nb_{2/3})O_3$–lead titanate $PbTiO_3$ solid solution (PMN–PT) are very suitable for application in actuators. This relaxor ferroelectrics can also provide an induced piezoelectric effect. That is, the electromechanical coupling factor k_t varies with the applied dc bias field. As the dc bias field increases, the coupling increases and saturates. This behavior is reproducible. These materials would be applied for ultrasonic transducers which can be tunable by the bias field (13).

Recently, single-crystal relaxor ferroelectrics have been developed which show great promising results in ultrasonic transducers and electromechanical actuators. Single crystals of $Pb(Mg_{1/3}Nb_{2/3})O_3$ (PMN), $Pb(Zn_{1/3}Nb_{2/3})O_3$ (PZN) and binary systems of these materials combined with $PbTiO_3$ (PMN–PT and PZN–PT) exhibit extremely large electromechanical coupling factors (14,15). Large coupling coefficients and large piezoelectric constants have been found for these solid-solution crystals with morphotropic phase boundary compositions. PZN-8%PT single crystals were found to possess high k_{33} value of 0.94 for (001) crystal cuts. The k_{33} value of the conventional PZT ceramics is usually 0.70 to 0.80.

More recently, it was reported that these relaxor based ferroelectric single crystals also exhibit ultrahigh strain levels not available with current piezoelectric ceramics (16). Pseudocubic ⟨001⟩ oriented relaxor based rhombohedral crystals such as $(1 - x)$PZN $-$ xPT ($x < 0.09$) and $(1 - x)$PMN $-$ xPT ($x < 0.35$) were reported to have $\boldsymbol{E}$-field induced strains up to 0.6% with negligible hysteresis. Ultrahigh strain levels more than 1.5%, nearly an order of magnitude higher than polycrystalline PZTs or electrostrictive PMN, could be achieved being related to an $\boldsymbol{E}$-field induced phase transformation.

APPLICATIONS OF PIEZOELECTRIC MATERIALS

Piezoelectric materials can provide coupling between electrical and mechanical energy and thus have been extensively used in a variety of electromechanical device applications. The direct piezoelectric effect is most obviously used in the generation of charge at high voltage such as for the spark ignition of gas in space heaters, cooking stoves, and cigarette lighters. Using the converse effect, mechanical small displacements and vibrations can be produced for actuators by applying a field. Acoustic and ultrasonic vibrations can be generated by an alternating field tuned at the mechanical resonance frequency of a piezoelectric device, and can be detected by amplifying the field generated by vibration incident on the material, which is usually used for ultrasonic transducers. The other important application field of piezoelectricity include the control of frequency. The application of piezoelectric materials ranges over many technology fields including ultrasonic transducers, actuators and ultrasonic motors, electronic components such as resonators, wave filters, delay lines, SAW devices and transformers, and high voltage applications; gas ignitors, ultrasonic cleaning, and machining. Piezoelectric-based sensors, for instance, accelerometers, automobile knock sensors, vibration sensors, strain gages, and flow meters have been developed, because pressure and vibration can be directly sensed as electric signals through piezoelectric effect. Examples of these applications are given in the following sections.

Ultrasonic Transducers

One of the most important applications of piezoelectric materials is based on ultrasonic echo field (17,18). Ultrasonic transducers convert electrical energy into mechanical form when generating an acoustic pulse and convert mechanical energy into an electrical signal when detecting its echo. Currently, piezoelectric transducers are being used in medical ultrasound for clinical applications ranging from diagnosis to therapy and surgery. They are also used for underwater detection, such as sonar and fish finding, and nondestructive testing.

The ultrasonic transducers often operate in a pulse-echo mode. The transducer converts electrical input into acoustic wave output. The transmitted waves propagate into a body and echoes are generated which travel back to be received by the same transducer. These echoes vary in intensity according to the type of tissue or body structure, thereby creating images. An ultrasonic image represents the mechanical properties of the tissue, such as density and elasticity. We can recognize anatomical structures in an ultrasonic image since the organ boundaries and fluid-to-tissue interfaces are easily discerned. The ultrasonic imaging process can also be done in real time. This means we can follow rapidly moving structures such as the heart without motion distortion. In addition, ultrasound is one of the safest diagnostic imaging techniques. It does not use ionizing radiation like x rays and thus is routinely used for fetal and obstetrical imaging. Useful areas for ultrasonic imaging include cardiac structures, the vascular systems, the fetus, and abdominal organs such as liver and kidney. In brief, it is possible to see inside the human body by using a beam of ultrasound without breaking the skin.

There are various types of transducers used in ultrasonic imaging. Mechanical sector transducers consist of single, relatively large resonators and can provide images by mechanical scanning such as wobbling. Multiple element array transducers permit discrete elements to be individually accessed by the imaging system and enable electronic focusing in the scanning plane to various adjustable penetration depths through the use of phase delays. Two basic types of array transducers are linear and phased (or sector). A linear array is a collection of elements arranged in one direction, producing a rectangular display. A curved linear (or convex) array is a modified linear array whose elements are arranged along an arc to permit an enlarged trapezoidal field of view. The elements of these linear type array transducers are excited sequentially group by group in a sweep of the beam in one direction. These linear array transducers are used for radiological and obstetrical examinations. On the other hand, in a phased array transducer the acoustic beam is steered by signals that are applied to the elements with delays, creating a sector display. This transducer is useful for cardiology applications where positioning between the ribs is necessary.

Figure 5 shows the basic ultrasonic transducer geometry. The transducer is mainly composed of matching layers, piezoelectric material and backing (19). One or more matching layers are used to increase sound transmissions into tissues. The backing is added to the rear of the transducer in order to damp the acoustic backwave and to reduce the pulse duration. Piezoelectric materials are used to generate and detect ultrasound. In general, broadband transducers should be used for medical ultrasonic imaging. The broad bandwidth response corresponds to a short pulse length, resulting in better axial resolution. Three factors are important in designing broad bandwidth transducers. The first is acoustic impedance matching, that is, effectively coupling acoustic energy to the body. The second is a high electromechanical coupling coefficient of the transducer. The third is electrical impedance matching, that is, effectively coupling electrical energy from the driving electronics to the transducer across the frequency range of interest. These pulse echo transducers operate based on the thickness mode resonance of the piezoelectric thin plate. The thickness mode coupling coefficient, k_t, is related to the efficiency of converting electric energy into acoustic and vice versa. Further, a low planar mode coupling coefficient, k_p, is beneficial for limiting energies being expended in nonproductive lateral mode. A large dielectric constant is necessary to enable a good electrical impedance match to the system, especially with tiny piezoelectric sizes.

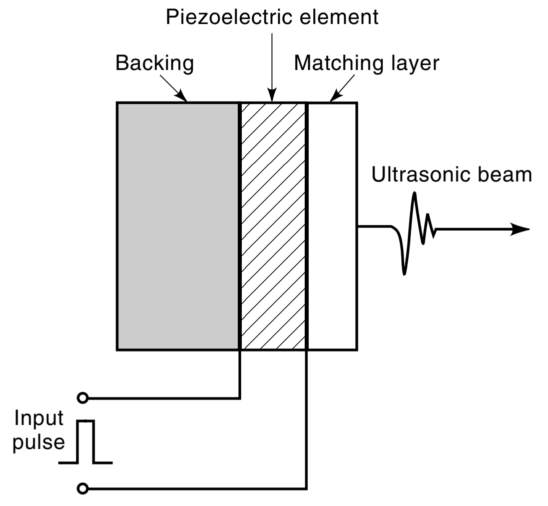

Figure 5. Prototype transducer geometry. The transducer is mainly composed of matching layer, piezoelectric material and backing.

Table 3 compares the properties of ultrasonic transducer materials (7,20). Ferroelectric ceramics, such as lead zirconate titanate and modified lead titanate, are today almost universally used as ultrasonic transducers. The success of ceramics is due to their very high electromechanical coupling coefficients. In particular, soft PZT ceramics such as PZT-5A and 5H type compositions are most widely used because of their exceedingly high coupling properties and because they can be relatively easily tailored, for instance, in the wide dielectric constant range. On the other hand, modified lead titanates such as samarium doped materials have high piezoelectric anisotropy: the planar coupling factor k_p is much less than the thickness coupling factor k_t. This absence of lateral coupling leads to reduced interference from spurious lateral resonances in longitudinal oscillators. This is very useful in high-frequency array transducer applications. One disadvan-

Table 3. Comparison of Ultrasonic Transducer Materials

	PZT Ceramic	PVDF Polymer	PZT-Polymer Composite	ZnO Film
k_t	0.45–0.55	0.20–0.30	0.60–0.75	0.20–0.30
Z (Mrayls)	20–30	1.5–4	4–20	35
$\epsilon_{33}^T/\epsilon_0$	200–5000	10	50–2500	10
$\tan\delta$ (%)	<1	1.5–5	<1	<1
Q_m	10–1000	5–10	2–50	10
ρ (g/cm^3)	5.5–8	1–2	2–5	3–6

tage to PZT and other lead based ceramics is their large acoustic impedance (approximately 30 Mrayls) compared to body tissue (1.5 Mrayls). Single or multiple matching layers with intermediate impedances needed to be used in the case of PZT to improve acoustic matching.

On the other hand, piezoelectric polymers, such as polyvinyliden-difluoride-trifluoroethylene, have much lower acoustic impedance (4 to 5 Mrayls) than the ceramics and thus provide better matching with soft tissues. However, piezopolymers are less sensitive than the ceramics and they have relatively low dielectric constants, requiring large drive voltage and giving poor noise performance due to electrical impedance mismatching.

An alternative to ceramics and polymers is piezoelectric ceramic/polymer composites. Piezocomposites having 2 to 2 or 1 to 3 connectivity are commonly used in ultrasonic medical applications. These combine the low acoustic impedance advantage of polymers with the high sensitivity and low electrical impedance advantages of ceramics.

The design frequency of a transducer depends on the penetration depth imposed by the application. Resolution is improved with increasing frequency. Although a high frequency transducer is capable of producing a high resolution image, higher frequency acoustic energy is more readily attenuated by the body. A lower frequency transducer is used as a compromise when imaging deeper structures. Most medical ultrasound imaging systems operate in the frequency range from 2 MHz to 10 MHz and can resolve objects approximately 0.2 mm to 1 mm in size. At 3.5 MHz, imaging to a depth of 10 cm to 20 cm is possible, while at 50 MHz, increased losses limit the depth to less than 1 cm. Higher-frequency transducers (10 MHz to 50 MHz) are used for endoscope-based imaging and for catheter-based intravascular imaging. At higher frequencies over 100 MHz applications are used in the field of ultrasound microscopy. The operating frequency of the transducer is directly related to the thickness and velocity of sound in the piezoelectric materials employed. As frequency increases resonator thickness decreases. For a 3.5 MHz transducer, PZT ceramic thickness needs to be roughly 0.4 mm. Most conventional ceramic transducers, such as PZT, are limited to frequencies below nearly 80 MHz because of the difficulty of fabricating thinner devices (21). For microscopic applications at frequencies over 100 MHz, corresponding to the thickness of less than 20 μm, piezoelectric thin-film transducers such as ZnO have to be used (22).

The design of ultrasonic transducers with piezoelectrics used in medical field was mentioned above. Another major ultrasonic transducer application is the underwater sonar transducer employed as both acoustic source and hydrophone. Sonar (sound navigation and ranging) is used to explore the ocean and underwater objects. Hydrophones are underwater microphones for detecting sound in water and under hydrostatic pressure. The representative transducers widely used for high-power and low-frequency active sonar include the Tonpilz and flextensional structures. The design of the Tonpilz transducer typically involves head and tail masses which are configured for impedance matching and a central piezoceramic section, whose shape roughly resembles a mushroom (23). This transducer is made from stacks of rings electroded on the flat surfaces and electrically connected in parallel and are electrically insulated for each other held together with a stress rod. On the other hand, the flextensional transducer uses a mechanical shell, generally made of metal such as steel or brass, to convert hydrostatic stress to a stress along one or more of the sensitive axes of a stack of piezoelectric ceramic plates or rings (24). The flextensional transducers with different shapes of the outer shell have been designed to achieve an extremely high sensitivity.

Actuators and Motors

Actuators. Currently the other important applications of piezoelectric materials exist in actuator fields (25). Actuators are defined as transducers capable of transferring input energy into a mechanical output energy. Using the converse piezoelectric effect, small displacement can be produced by applying a field to piezoelectric materials. Vibrations can be generated by applying an alternating field. In advanced precision engineering, the demand for a variety of types of actuators which can adjust positions precisely (micropositioning devices), suppress noise vibrations (dampers), or drive objects dynamically (ultrasonic motors) exist. These devices are used in broad areas including optics, astronomy, fluid control, and precision machinery. For actuator applications, piezoelectric strain and electrostriction induced by an electric field are used. Electrostrictive materials such as lead magnesium niobate (PMN) ceramics are especially preferred because of their small degradation under severe operating conditions. The PMN is easily electrically poled when an electric field is applied around the transition temperature and depoled completely without any remanent polarization. This provides extraordinarily large apparent electrostriction though it is a secondary phenomenon of the electromechanical coupling. Figure 6 shows the longitudinal induced strain curve at room temperature in 0.9PMN–0.1PT (26). The magnitude of the electrostriction is 10^{-3} and this material has almost no hysteresis.

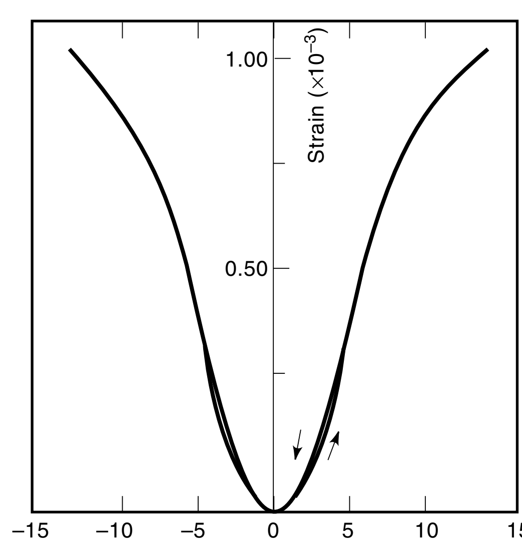

Figure 6. Longitudinal induced strain curve at room temperature in 0.9PMN–0.1PT as a function of electric field. The magnitude of the electrostriction is 10^{-3} and this has almost no hysteresis.

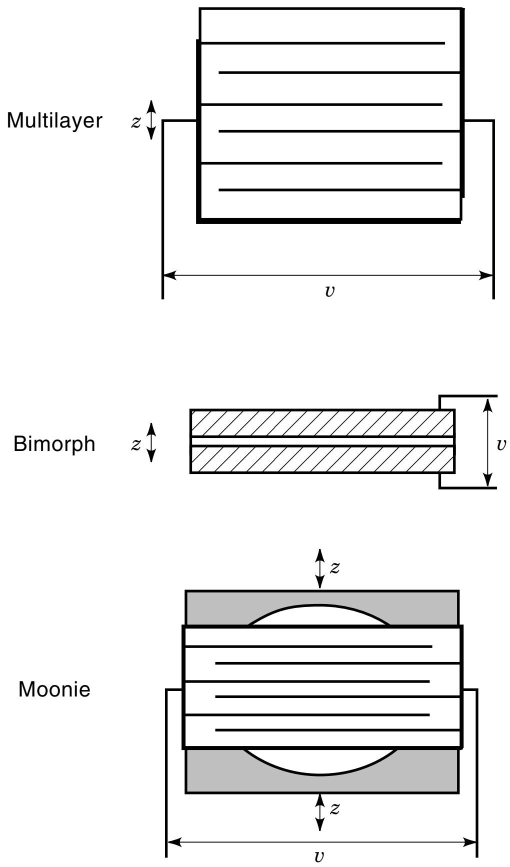

Figure 7. Structures of ceramic actuators. There are three representative types: multilayer, bimorph, and moonie types.

Figure 7 shows the design classification of ceramic actuators. Simple devices composed of a disk and multilayer type directly use the strain induced in a ceramic by the applied electric field. Complex devices do not use the induced strain directly but use the magnified displacement through a special magnification mechanism such as unimorph, bimorph, and moonie. The most popularly used multilayer and bimorph types have the following characteristics: The multilayer type does not show a large displacement (10 μm), but has advantages in generation force (1000 N), response speed (10 μs), lifetime (10^{11} cycles), and the electromechanical coupling factor k_{33} (0.70). The bimorph type exhibits a large displacement (300 μm), but shows disadvantages in generation force (1 N), response speed (1 ms), lifetime (10^8 cycles) and the electromechanical coupling factor k_{eff} (0.10). For instance, in a 0.65 PMN–0.35 PT multilayer actuator with 99 layers of 100 μm thick sheets ($2 \times 3 \times 10$ mm^3), an 8.7 μm displacement is generated by a 100 V voltage, accompanied by a slight hysteresis. The transmit response of the induced displacement after the application of a rectangular voltage is as quick as 10 μs. In conclusion, the multilayer exhibits the field induced strain of 0.1% along the length.

Unimorph and bimorph devices are defined by the number of piezoelectric ceramic plates: only one ceramic plate is bonded onto an elastic shim, or two ceramic plates are bonded together simultaneously. The bimorph causes bending deformation because each piezoelectric plate bonded together produces extension or contraction under an electric field. In general, there are two types of piezoelectric bimorph: antiparallel polarization type and parallel polarization type, as shown in Fig. 8. Two poled piezoelectric plates with $t/2$ in thickness and L in length are bonded with their polarization directions opposite or parallel to each other. In cantilever bimorph configuration whose one end is clamped, the tip displacement δ_z under an applied voltage V is provided as follows

$$\delta_z = 3/2 \cdot d_{31}(L^2/t^2)V \quad \text{(antiparallel type)} \tag{9}$$

$$\delta_z = 3d_{31}(L^2/t^2)V \quad \text{(parallel type)} \tag{10}$$

The resonance frequency f_r for both types is given by

$$f_r = 0.16t/L^2\,(\rho S_{11}^E)^{-1/2} \tag{11}$$

where ρ is density and S_{11}^E is elastic compliance. A metallic sheet (called a shim) is occasionally sandwiched between the two piezoelectric plates to increase the reliability, that is, the structure can be maintained even if the ceramics fracture. Using the bimorph structure, a large magnification of the displacement is easily obtainable. However, the disadvantages include a low response speed (1 kHz) and low generative force.

A composite actuator structure called moonie has been developed to amplify the small displacements induced in a piezoelectric ceramic. The moonie consists of a thin multilayer element and two metal plates with a narrow moon-shaped cavity bonded together. This device has intermediate characteristics between the conventional multilayer and bimorph actuators; this shows an order of magnitude larger displacement (100 μm) than the multilayer, and much larger generative force (100 N) with quicker response (100 μs) than the bimorph.

Some examples of applications of piezoelectric and electrostrictive actuators mentioned already are described next. The piezoelectric impact dot-matrix printer is the first mass-produced device using multilayer ceramic actuators. The advantage of the piezoelectric printer head compared to the conventional magnetic types are: low energy consumption, low heat generation, and fast printing speed. The longitudinal multilayer actuators do not exhibit a large displacement and thus a suitable displacement magnification mechanism is necessary. The displacement induced in a multilayer actuator pushes up the force point, and its displacement magnification is carried out through hinge levers so as to generate a large wire stroke. When the displacement in the piezoactuator is 8

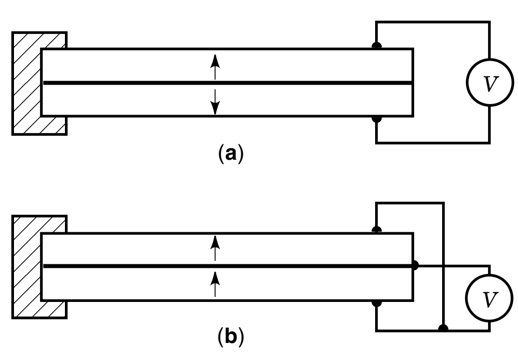

Figure 8. Two types of piezoelectric bimorphs: (a) antiparallel polarization type and (b) parallel polarization type.

μm, the wire stroke of 240 μm can be obtained, that is the magnification rate is 30 times.

Bimorph structures are commonly used for VCR head tracking actuators, because of their large displacements. An autotracking scan system uses the piezoelectric actuators so that the head follows the recording track even while driven at both still and quick modes. As can be anticipated, the bimorph drive is inevitably accompanied by a torsional motion. To obtain a perfect parallel motion a special mechanism has to be employed. Piezoelectric bimorphs have also been used in phonograph pick-up cartridges, and cantilever bimorphs with small masses attached to their free end can be used as accelerometers. Piezoelectric pumps for gas or liquid utilizing an alternating bending motion of bimorph have been developed for intravenous drip injection in hospitals and for medication dispensers in chemotherapy, chronic pain, and diabetes. Piezoelectric fans for cooling electronic circuits are made from a pair of bimorphs which are driven out of phase so as to blow effectively. Furthermore, piezo-bimorph type camera shutters have been widely commercialized.

In optical control systems, lenses and mirrors require micropositioning and even the shapes of mirrors are adjusted to correct image distortions. For instance, a space qualified active mirror called articulating fold mirror utilizes six lead magnesium niobate (PMN) electrostrictive multilayer actuators to precisely position a mirror tip and tilt in order to correct the focusing aberration of the Hubble Space Telescope.

Piezoelectric actuators are also useful for vibration suppression systems of an automobile. An electronic controlled shock absorber was developed by Toyota. The piezoelectric sensors detecting road roughness is composed of 5 layers of 0.5 mm thick PZT disks. The actuator is made of 88 layers of 0.5 mm thick disks. Applying 500 V generates about 50 μm displacement, which is magnified by 40 times through a piston and plunger pin combination. This stroke pushes the change valve of the damping force down, then opens the bypass oil route, leading to decrease in the flow resistance. This electronically controlled shock absorber has both controllability and comfortablility simultaneously.

Ultrasonic Motors. An ultrasonic motor is an example of piezoelectric actuators using a resonant vibration. In ultrasonic motors linear motion is obtained from the elliptical vibration through frictional force. The motor basically consists of a high-frequency power supply, a vibrator, and a slider. The vibrator is composed of a piezoelectric driving component and an elastic vibrator part, and the slider is composed of an elastic moving part and a friction coat. The characteristics of the ultrasonic motors are low speed and high torque compared to the conventional electromagnetic motors with high speed and low torque (25,27).

The ultrasonic motors are classified into two types: a standing-wave type and a propagating-wave type. The standing wave is expressed by

$$Vs(x,t) = A\cos(kx)\cdot\cos(\omega t) \quad (12)$$

while the propagation wave is given by

$$\begin{aligned} Vp(x,t) &= A\cos(kx-\omega t) \\ &= A\cos(kx)\cdot\cos(\omega t) + A\cos(kx-\pi/2)\cdot\cos(\omega t-\pi/2) \end{aligned} \quad (13)$$

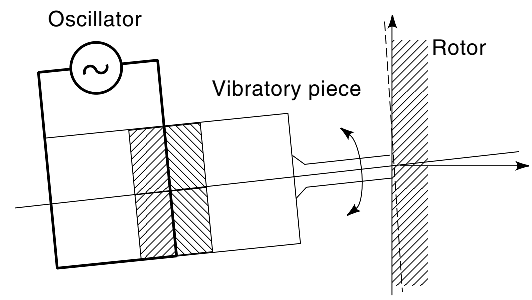

Figure 9. Vibratory coupler type ultrasonic motor. A vibratory piece is attached to a rotor or a slider with a slight cant angle.

A propagating wave can be generated by superimposing two standing waves whose phases differ by 90° to each other both in time and in space. The standing-wave type is sometimes known as a vibratory-coupler or a "woodpecker" type, where a vibratory piece is connected to a piezoelectric driver and the tip portion generates flat-elliptic movement. Figure 9 shows a vibratory coupler type motor. A vibratory piece is attached to a rotor or a slider with a slight cant angle. The standing-wave type has high efficiency, up to 98% theoretical. However, a problem of this type is lack of control in both clockwise and counterclockwise directions. The principle of the propagation type is shown in Fig. 10. In the propagating-wave type, also called "surfing-type," a surface particle of the elastic body draws an elliptic locus due to the coupling of longitudinal and transverse waves. This type generally requires two vibration sources to generate one propagating wave, leading to low efficiency (not more than 50%), but is controllable in both the rotational directions. An ultrasonic rotatory motor is successfully used in autofocusing cameras to produce precise rotational displacements. The advantages of this motor over the conventional electromagnetic motor are: silent drive (inaudible), thin motor design, and energy saving.

Resonators and Filters

When a piezoelectric body vibrates at its resonant frequency it absorbs considerably more energy than at other frequencies resulting in the fall of impedance. This phenomenon enables piezoelectric materials to be used as a wave filter. A filter is required to pass a certain selected frequency band or to stop a given band. The bandwidth of a filter fabricated from a piezoelectric material is determined by the square of the coupling coefficient k, that is, nearly proportional to k^2. Quartz

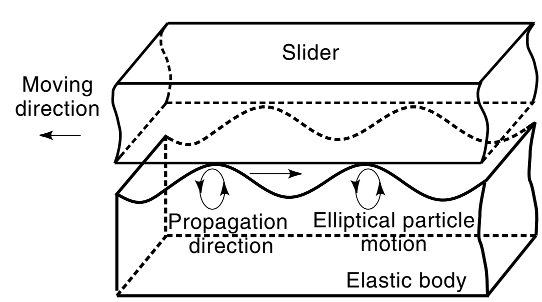

Figure 10. Principle of the propagating wave type ultrasonic motor. A surface particle of the elastic body draws an elliptic locus due to the coupling of longitudinal and transverse waves.

crystals with very low k value of about 0.1 can pass very narrow frequency bands of approximate 1% of the center resonance frequency. On the other hand, PZT ceramics with a planar coupling coefficient of about 0.5 can easily pass a band of 10% of the center resonance frequency. The sharpness of the passband is dependent on the mechanical quality factor Q_m of the materials. Quartz has also a very high Q_m of about 10^6 which results in a sharp cut-off to the passband and well-defined frequency of the oscillator.

A simple resonator is a thin disk type, electroded on its plane faces and vibrating radially for applications in filters with a center frequency ranging from 200 kHz to 1 MHz and with a bandwidth of several percent of the center frequency. For a frequency of 455 kHz the disk diameter needs to be about 5.6 mm. However, if the required frequency is higher than 10 MHz, other modes of vibration such as the thickness extensional mode are exploited, because of its smaller size disk. The trapped-energy type filters made from PZT ceramics have been widely used in the intermediate frequency range for such as 10.7 MHz for FM radio receiver and transmitter. By employing the trapped-energy phenomena, the overtone frequencies are suppressed. The plate is partly covered with electrodes of a specific area and thickness. The fundamental frequency of the thickness mode beneath the electrode is less than that of the unelectroded portion, because of the extra inertia of the electrode mass. The longer wave characteristic of the electrode region cannot propagate in the unelectroded region. The higher-frequency overtones can propagate away into the unelectroded region. This is known as trapped-energy principle. Figure 11 shows a schematic drawing of trapped-energy filter. In this structure the top electrode is split so that coupling between the two parts will only be efficient at resonance. More stable filters suitable for telecommunication systems have been made from single crystals such as quartz or $LiTaO_3$.

SAW Devices

A surface acoustic wave (SAW) also called a Rayleigh wave is composed of a coupling between longitudinal and shear waves in which the SAW energy is confined near the surface. An associated electrostatic wave exists for a SAW on a piezoelectric substrate, which allows electroacoustic coupling via a transducer. The advantages of SAW technology are that the wave can be electroacoustically accessed and tapped at the substrate surface and its velocity is approximately 10^4 times slower than an electromagnetic wave. The SAW wavelength is on the same order of magnitude as line dimensions which can be photolithographically produced and the lengths for both short and long delays are achievable on reasonable size substrates (28,29).

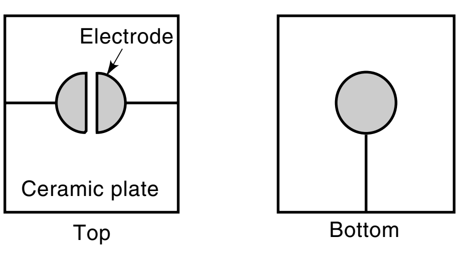

Figure 11. Trapped-energy type filter. The top electrode is split so that coupling between two parts will only be efficient at resonance.

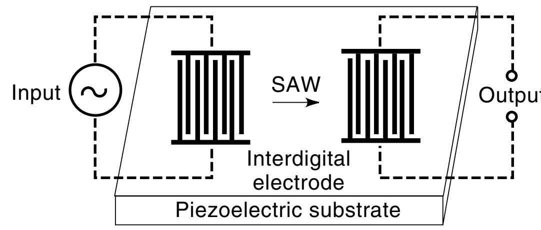

Figure 12. Typical SAW bidirectional filter consisting of two interdigital transducers. The input transducer generates surface acoustic waves in either direction and the output transducer converts the acoustic energy back to an electrical signal.

There are a very broad range of commercial system applications which include front-end and IF (intermediate frequency) filters, CATV (community antenna television) and VCR (video cassette recorder) components, synthesizers, analyzers, and navigators. In SAW transducers, finger electrodes provide the ability to sample or tap the wave and the electrode gap gives the relative delay. A SAW filter is composed of a minimum of two transducers. A schematic of a simple SAW bidirectional filter is shown in Fig. 12. A bidirectional transducer radiates energy equally from each side of the transducer. Energy not being received is absorbed to eliminate spurious reflection.

Various materials are currently being used for SAW devices. The most popular single-crystal SAW materials are lithium niobate and lithium tantalate. The materials have different properties depending on the cut of the material and the direction of propagation. The fundamental parameters considered when choosing a material for a given device applications are SAW velocity, temperature coefficients of delay (TCD), electromechanical coupling factor, and propagation loss. Surface acoustic waves can be generated and detected by spatially periodic, interdigital electrodes on the plane surface of a piezoelectric plate. A periodic electric field is produced when a radio frequency (RF) source is connected to the electrode, thus permitting piezoelectric coupling to a traveling surface wave. If an RF source with a frequency, f, is applied to the electrode having periodicity, d, energy conversion from an electrical to mechanical form will be maximum when

$$f = f_0 = V_s/d \tag{14}$$

V_s is the SAW velocity and f_0 is the center frequency of the device. SAW velocity is an important parameter determining the center frequency. Another important parameter for many applications is temperature sensitivity. For example, the temperature stability of the center frequency of SAW bandpass filters is a direct function of temperature coefficient for the velocity and delay for the material used. The first-order temperature coefficient of delay is given by

$$(1/\tau)\cdot(d\tau/dT) = (1/L)\cdot(dL/dT) - (1/V_s)\cdot(dV_s/dT) \tag{15}$$

where $\tau = L/V_s$ is the delay time and L is the SAW propagation length. The surface wave coupling factor, k_s^2, is defined in terms of the change in SAW velocity which occurs when the wave passes across a surface coated with a thin massless con-

Table 4. SAW Material Properties

	Material	Cut-Propagation Direction	k^2 (%)	TCD (ppm/C)	V_0 (m/s)	ϵ_r
Single crystal	Quartz	ST–X	0.16	0	3158	4.5
	$LiNbO_3$	128°Y–X	5.5	−74	3960	35
	$LiTaO_3$	X112°–Y	0.75	−18	3290	42
	$Li_2B_4O_7$	(110)–⟨001⟩	0.8	0	3467	9.5
Ceramic	PZT-In($Li_{3/5}W_{2/5}$)O_3		1.0	10	2270	690
	(Pb,Nd)(Ti,Mn,In)O_3		2.6	<1	2554	225
Thin film	ZnO/glass		0.64	−15	3150	8.5
	ZnO/Sapphire		1.0	−30	5000	8.5

ductor, so that the piezoelectric field associated with the wave is effectively shorted-circuited. The coupling factor, k_s^2, is expressed by

$$k_s^2 = 2(V_f - V_m)/V_f \qquad (16)$$

where V_f is the free surface wave velocity, and V_m the velocity on the metallized surface. In actual SAW applications, the value of k_s^2 relates to the maximum bandwidth obtainable and the amount of signal loss between input and output, determining the fractional bandwidth versus minimum insertion loss for a given material and filter. Propagation loss is one of the major factors that determine the insertion loss of a device and is caused by wave scattering at crystalline defects and surface irregularities. Materials which show high electromechanical coupling factors combined with small temperature coefficients of delay are likely to be required. The free surface velocity, V_0, of the material is a function of cut angle and propagation direction. The TCD is an indication of the frequency shift expected for a transducer due to a temperature change and is also a function of cut angle and propagation direction. The substrate is chosen based on the device design specifications and includes consideration of operating temperature, fractional bandwidth, and insertion loss.

Piezoelectric single crystals such as 128°Y–X (128°-rotated-Y-cut and X-propagation) - $LiNbO_3$ and X–112°Y (X-cut and 112°-rotated-Y-propagation) - $LiTaO_3$ have been extensively employed as SAW substrates for applications in VIF (video intermediate frequency) filters. A c-axis oriented ZnO thin film deposited on a fused quartz, glass, or sapphire substrate is also commercialized for SAW devices. Table 4 shows some important material parameters for some SAW materials.

Delay Lines

A delay line can be formed from a slice of glass such as PbO or K_2O doped SiO_2 glass in which the velocity of sound is nearly independent of temperature. PZT ceramic transducers are soldered on two metallized edges of the slice of glass. The input transducer converts the electrical signal to a shear acoustic wave which travels through the slice. At the output transducer the wave is reconverted into an electrical signal delayed by the length of time taken to travel around the slice. Such delay lines are used in color TV sets to introduce a delay of approximately 64 μs and are also employed in videotape recorders.

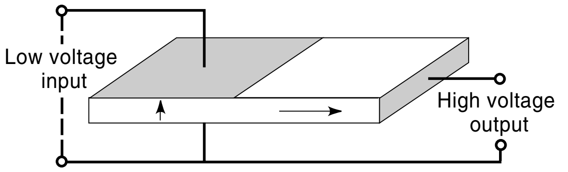

Figure 13. Fundamental Rosen-type structure of piezoelectric transformer. Two differently-poled parts coexist in one piezoelectric plate.

Piezoelectric Transformer

The transfer of vibration energy from one set of electrodes to another on a piezoelectric ceramic body can be used for voltage transformation. This device is called a piezoelectric transformer. Recently, office automation equipment with liquid crystal displays have been successfully commercialized into such products as notebook type personal computers and car navigation systems. This equipment with a liquid crystal display requires a very thin, no electromagnetic-noise transformer to start the glow of a fluorescent back-lamp. This application has recently accelerated the development of piezoelectric transformers. Figure 13 shows a fundamental structure where two differently poled parts coexist in one piezoelectric plate. The plate has electrodes on half its major faces and on an edge, which is then poled in its thickness direction at one end and parallel to the long axis over most of its length. A low-voltage ac supply is applied to the large-area electrodes at a frequency that excites a length extensional mode resonance. A high-voltage output can then be taken from the small electrode and one of the larger electrodes. After the proposal by C. A. Rosen, piezoelectric transformers with several different structures have been reported. A multilayer type transformer is proposed in order to increase the voltage rise ratio. The input part is of the multilayer structure with internal electrodes and the output electrodes are formed at the side surface of the rectangular plate. This transformer uses piezoelectric transverse mode for the input and output parts.

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YUKIO ITO
KENJI UCHINO
The Pennsylvania State University

PIEZOELECTRIC OSCILLATIONS. See SPACE CHARGE.
PIEZOELECTRICS. See PIEZOELECTRICITY.
PIEZOELECTRIC SURFACE ACOUSTIC WAVE DEVICES. See SURFACE ACOUSTIC WAVE DEVICES.
PIEZOELECTRIC THIN FILMS. See THIN FILMS.