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Piezoelectric Materials and Their Applications

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Piezoelectric Materials and Their Applications

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Abstract: Over 100 years ago, Jacques and Pierre Curie experimentally confirmed the presence of the piezoelectric effect in quartz, Rochelle salts and tourmaline single crystals. Within the last 50 years, a number of ceramic and polymer materials with non-symmetrical crystal structures have also been found to exhibit the piezoelectric effect. The discovery of strong piezoelectricity in these materials has led to their commercialization and has been a major factor in the development of a wide range of applications. This paper begins with a review of the fundamental properties of piezoelectric materials. A description of the important types of piezoelectric materials and their characteristics are presented next, followed by discussions of selected applications, with additional applications listed in tabular format.

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3. PIEZOELECTRIC MATERIALS AND CHARACTERISTICS

3.1 Piezoelectric Crystals

The notion that electricity could be produced in some crystals by subjecting them to mechanical pressure is believed to have been suggested by Charles Coulomb [7]. Subsequent investigations by Haüy [8] and Becquerel [9] prior to 1825 hinted that this pressure-electric effect was a possibility, however, irrefutable evidence of the effect did not emerge for about six decades. This evidence was provided by the research efforts of Jacques and Pierre Curie [10] in 1880 at the University of Paris, while studying crystals such as quartz, sodium potassium tartrate (Rochelle salt), and tourmaline. By placing weights on the faces of particular crystal cuts, like the X cut quartz plate shown in Fig. 9, they succeeded in detecting charges on the crystal surfaces and demonstrated that the magnitude of charge was proportional to the applied weight, thus verifying the direct pressure-electric effect.

The converse pressure-electric effect, that is the development of a mechanical strain when an electric field is applied to a crystal such as quartz, was predicted in 1881 by Lippmann [11] who based his theory on fundamental thermodynamic principles. In the same year, this theoretical converse effect was supported experimentally by the Curies [12]. Shortly after these works on the converse effect were published, Hankel suggested the name "piezoelectricity" to describe the effect, with "piezo" being a Greek derivative meaning "to press" [7]. Thus the terms direct and converse piezoelectric effects were introduced into the literature and have been entrenched therein for more than a century.

Theoretical advances in understanding piezoelectricity in crystals were made during the late 1800s and early 1900s by the pioneering efforts of Lord Kelvin [13], Pierre Duhem [14], Friedrich Pockels [15], and Woldemar Voigt [16]. Indeed, *Lehrbuch der Krystallophysik*, the classic work of Voigt [17], became the foundation for a great deal of research in the field of piezoelectricity in the twentieth century.

Significant experimental contributions to the evolution and exploitation of the piezoelectric effect came from the field of crystallography, which received an enormous boost in 1912 with the discovery that crystals could act as three-dimensional X-ray diffraction gratings. This led to a number of studies that linked observed piezoelectric properties to internal crystalline structures. An example of such a study on the quartz crystal was published by Bragg and Gibbs [18].

Another concept that would play a useful role in the development of piezoelectric devices was that of the equivalent circuit. Butterworth [19] first realized that vibrating mechanical systems sustained by electrical currents or voltages could be represented by lumped-parameter electrical circuits consisting of inductors, capacitors, and resistors. It was Cady [20] and Van Dyke [21], colleagues at Wesleyan University in Middletown, Connecticut, who first derived the equivalent circuit shown in Fig. 10 for the piezoelectric resonator at an isolated resonance frequency. In this circuit, a clamped capacitance C_0 representing the dielectric property of the resonator is placed in parallel with a motional arm consisting of L_1 , C_1 , and R_1 , representing the inertial, elastic, and frictional properties of the resonator, respectively. These four parameters are assumed to be independent of frequency. In terms of the circuit parameters, the resonance frequency, the mechanical quality factor Q_M which represents the dissipation at resonance, and the -3 dB bandwidth (BW) are given by the following expressions:

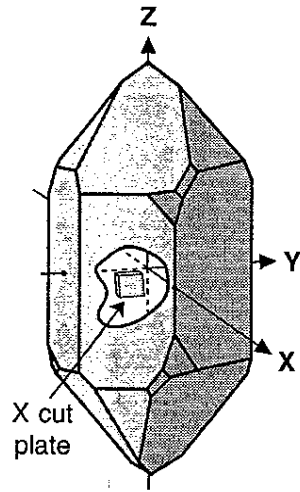


Figure 9: Right-handed quartz crystal and an X cut plate.

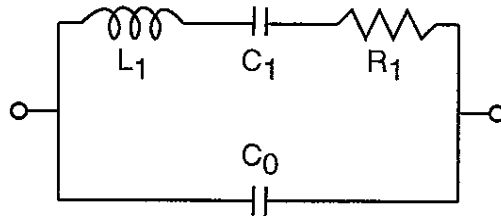


Figure 10: Equivalent circuit of a piezoelectric resonator.

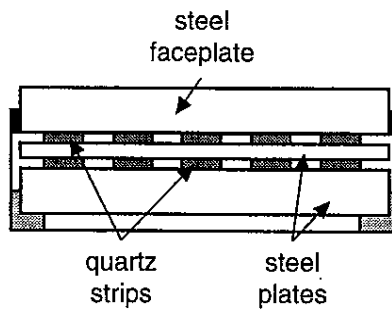


Figure 11: Quartz-steel sandwich transducer.

$$F_r = \frac{1}{2\pi} \sqrt{\frac{1}{L_1 C_1}} \quad (37)$$

$$Q_M = \frac{\sqrt{L_1 C_1}}{R_1} \quad (38)$$

$$BW = \frac{F_r}{Q_M} \quad (39)$$

Hence, the direct correspondences between mechanical and electrical quantities, such as mass and inductance or compliance and capacitance, allow the designer of electromechanical devices and systems to formulate appropriate equivalent circuits that can be analyzed using the well-known laws, theorems, and procedures established in electrical circuit theory.

The first application of the piezoelectric effect was a force and charge measuring apparatus patented by the Curies [22] in 1887. They used the piezoelectric effect to measure voltages and forces by constructing bimorphs from two X cut quartz plates of opposite polarity. The bimorphs consisted of two plates bonded together and electrically excited in such a way that each plate deformed in the opposite direction, resulting in a net bimorph bending motion. The deflections of the bimorph were much greater than the displacements of single quartz plates. Observations of these bimorph deflections using a microscope, and measurements of the charge on the bimorph when it was mechanically deformed, permitted the measurements of voltages and forces, respectively. Other applications for the piezoelectric effect in crystals would have to wait for about thirty years.

In early 1917 the first piezoelectric quartz transducers for underwater echo ranging and depth sounding were built by Paul Langevin at the School of Industrial Physics and Chemistry in Paris [23]. Using high-frequency vacuum tube amplifiers and quartz-steel sandwich transducers, Langevin was able to detect echos from submarines at ranges exceeding one kilometer in 1918. Depth sounding equipment based on Langevin's ultrasonic quartz-steel transducers became commercially available in Great Britain and the United States by 1925. A cross-section of a quartz-steel sandwich transducer is shown in Fig. 11. Two layers of thin quartz strips were separated by a center plate and sandwiched between two relatively massive steel plates. The outside surface of the top plate is the radiating face.

Synthetically grown crystals of Rochelle salt and ammonium dihydrogen phosphate (ADP) followed quartz as the active materials of choice for underwater transducers [24, 25]. Sketches of these crystals are shown in Fig. 12. Rochelle salt and ADP are ferroelectric since they exhibit spontaneous polarizations that can be reversed by the application of an applied electric field. Along with their related tartrates and isomorphs, these crystals were the only two types of ferroelectric materials known until the early 1940s.

In 1919, Nicolson [26] demonstrated the use of Rochelle salt crystals in loudspeakers, microphones, telephone receivers, and phonograph pick-ups. A stereo phonograph pick-up head utilizing Rochelle salt bender elements (i.e. bimorphs) is illustrated in Fig. 13. In this figure, the pick-up is drawn vertically and the view is looking up at the stylus from the surface of the record disc. The stylus vibrations, generated from signals recorded on the walls of the record grooves

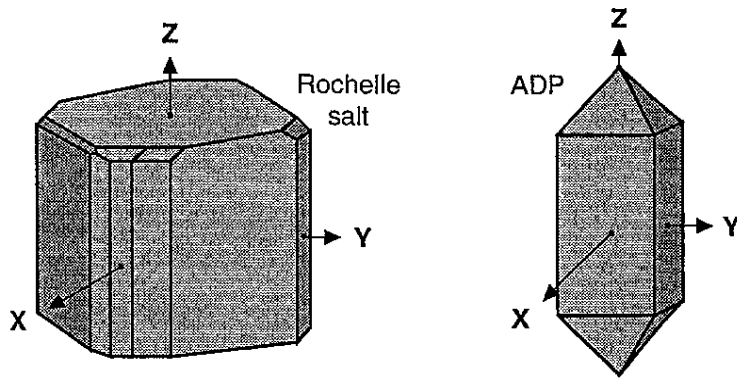


Figure 12: Crystals of Rochelle salt and ADP.

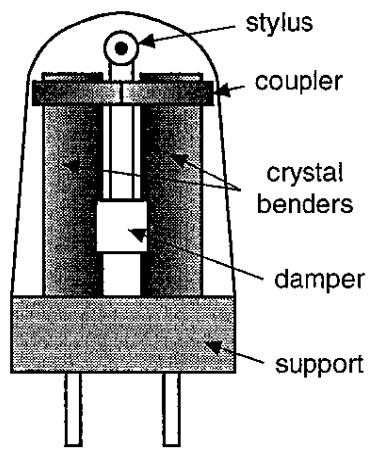


Figure 13: Rochelle salt crystal phonograph pick-up (bottom view).

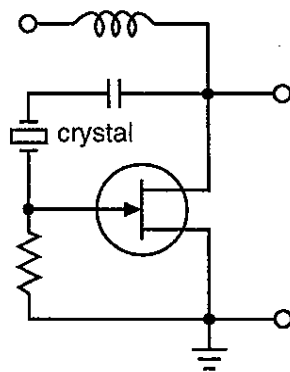


Figure 14: Pierce crystal oscillator.

plus the rotation of the record itself, are coupled into the crystal benders and converted into electrical signals.

The field of crystal controlled oscillators began in the early 1920s with the pioneering efforts of Cady [20] and Pierce [27] using high Q piezoelectric quartz resonators. Quality factors exceeding a million can be achieved in these oscillators. The importance of these devices to radio transmitters and receivers led to a number of important patents and associated patent interferences, with legal battles that lasted for more than three decades [28]. Furthermore, the need for large quantities of pure quartz crystals was so great for communications applications that natural sources became strained with the demand. This sparked many researchers to investigate growing techniques for quartz [29]. Today, cultured quartz oscillators are used primarily by the electronics industry in applications ranging from computer clocks and wrist-watches to radio and television broadcasting, which is testimony to the stability and reliability of the quartz resonator. An example of a Pierce crystal oscillator is shown in Fig. 14. The crystal in this field-effect transistor circuit acts as an electromechanical positive feedback component, providing maximum drain-to-gate feedback at the series-resonance frequency of the crystal, given by Eq. 37. More details on this circuit can be found in Matthews [30].

Another important field for piezoelectric crystals is that of selective wave filters. Again, high-Q low-dissipation quartz crystals are ideal for creating sharp attenuation slopes in various types of filters, many of which are discussed by Mason [31]. Crystal filters were first used primarily by the radio and telephone communication industries but today they are found in paging equipment, frequency synthesizers, navigation systems, and control systems. Multi-pole filters, such as the simple two-pole bandpass crystal filter illustrated in Fig. 15, are discussed in detail in Smythe and Wagers [32].

Piezoelectric quartz crystal transducers were used extensively in delay lines for moving-target indicator radar systems in the 1940s [33]. In these systems, moving and stationary targets were distinguished by storing a radar pulse in a delay line and comparing it to subsequent pulses. Using this methodology, moving targets were prominently displayed on a plan-position indicator display while stationary targets were suppressed. Delay lines were also used in digital computers and colour televisions. A typical delay line, illustrated in Fig. 16, can provide signal delays from a few tens of microseconds to several milliseconds [34]. Basically, a transmitting X cut quartz plate, excited by a signal pulse, generates an acoustic wave that travels through a delay medium and is received by a second X cut quartz plate after a time determined by the sound speed and length of the delay medium. Acoustic delay line materials include tubes filled with liquid mercury and solid rods of fused silica.

The piezoelectric quartz transducer was also employed as an ultrasonic wave transmitter in an acoustic interferometer described by Pierce in 1925 [35]. By generating standing waves between the crystal transducer and a movable reflector, this instrument was capable of measuring velocity and attenuation as a function of composition and temperature in a variety of gases and liquids. A sketch of an acoustic interferometer is shown in Fig. 17. Thus, as the Curies had discovered 40 years earlier, piezoelectric crystals offered scientific investigators new experimental techniques that could be used to great advantage in their research laboratories.

The material properties for two piezoelectric crystals are listed in Table 3. The elastic compliance, piezoelectric strain, and electric permittivity constants, determined by standard resonance methods [36], are given for piezoelectric α -quartz (SiO_2) [37] and ferroelectric lithium niobate (LiNbO_3) [38]. In the field of precision frequency control, hydrothermally grown quartz

Table 3: Properties of Piezoelectric Crystals

Material Constants	Units	SiO ₂ ^a	LiNbO ₃ ^b
Density	<i>kg/m³</i>		
ρ		2650	4640
Compliance	<i>10⁻¹²m²/N</i>		
s_{11}^E		12.77	5.831
s_{33}^E		9.60	5.026
s_{44}^E		20.04	17.10
s_{12}^E		- 1.79	- 1.150
s_{13}^E		- 1.22	- 1.452
s_{14}^E		- 4.50	- 1.00
Piezoelectric	<i>10⁻¹² C/N</i>		
d_{11}		2.31	-
d_{22}		-	20.8
d_{33}		-	6.0
d_{14}		- 0.727	-
d_{15}		-	69.2
d_{31}		-	- 0.85
Permittivity	<i>10⁻¹⁰ F/m</i>		
ϵ_{11}^T		0.3997	7.538
ϵ_{33}^T		0.4103	2.543

^a From Ref. 37

^b From Ref. 38

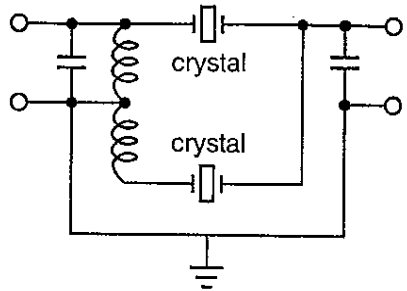


Figure 15: Narrow band crystal filter.

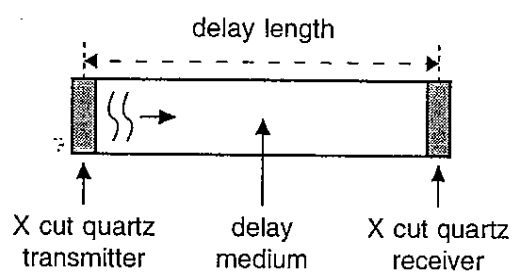


Figure 16: Delay line with quartz transducers.

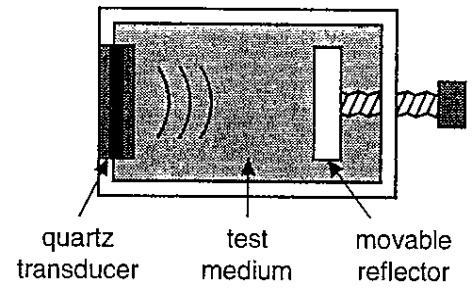


Figure 17: An acoustic interferometer.

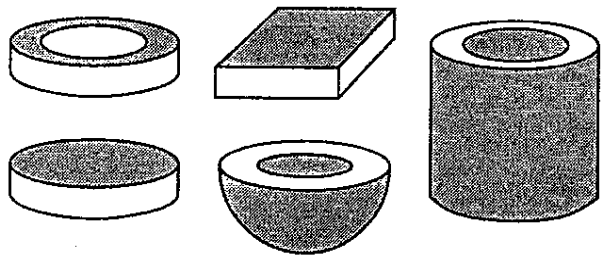


Figure 18: Piezoelectric ceramic shapes.

crystals are widely used for bulk-acoustic-wave (BAW) resonators [39] while crystals of lithium niobate (grown from the melt), lithium tantalate, bismuth germanium oxide, and α -quartz are used for surface-acoustic-wave (SAW) resonators [39, 40]. The properties for many other piezoelectric and ferroelectric crystals can be found in Auld [41].

3.2 Piezoelectric Ceramics

Jaffe, Cook, and Jaffe [42] have reviewed the discovery and development of the first polycrystalline piezoelectric ceramic, barium titanate (BaTiO_3), which took place in the 1940s. They pointed out that three key areas of investigation were responsible for our understanding of the piezoelectric effect in this ceramic. First of all, although barium titanate perovskites had been known since the 1920s [43], the discovery of high dielectric constants in various barium and titanium oxide compositions in 1941 [44] became the catalyst for further research on these materials. Secondly, by the mid 1940s it was realized that the high dielectric constant observed in barium titanate ceramic was a consequence of ferroelectricity [45, 46]. Finally, it was demonstrated that isotropic samples of ferroelectric barium titanate ceramic could be made piezoelectric, and necessarily anisotropic, by applying a large electric field at an elevated temperature, thereby creating an internal remnant polarization that persists long after the removal of the electric and thermal fields [47, 48]. This process, known as poling in the ceramics industry, was the revolutionary finding that signaled the decline of piezoelectric crystal use in many applications.

One of the significant advantages of piezoelectric ceramics over piezoelectric crystals is the ability to form ceramics into a variety of shapes and sizes. Discs, rings, washers, cylinders, tubes, bars, plates, and hemispheres are some of the possibilities (see Fig. 18). When combined with the freedom to determine the poling direction and electrode configuration, ceramics manufacturers possess great versatility to tailor ceramic components for specific device requirements.

Barium titanate was first used for phonograph pick-ups in 1947, replacing Rochelle salt crystal pick-ups used since about 1935 [42]. In the field of instrumentation standards, barium titanate accelerometers and accelerometer calibration shakers were developed in the early 1950s to support improvements to missile guidance systems [49, 50]. Barium titanate was also used in the medical field in the late 1950s for intracardiac phonocatheters [51, 52]. Non-piezoelectric applications for barium titanate included monolithic multilayer ceramic capacitors [53], and positive temperature coefficient resistors for overload protection devices [53] and heating elements [54].

By 1948, applications for barium titanate ceramic in the field of sonar included cylindrical hydrophones for radio sonobuoys, and piston and cavity projectors to replace crystal and magnetostrictive projectors [55]. In the beginning, barium titanate was substituted for quartz in the Langevin sandwich transducer shown in Fig. 11. For example, in 1951 a 50 kHz barium titanate Langevin transducer was used in a fish finder and successfully located the first school of fish in Japan [56]. It soon became apparent that barium titanate transducers could achieve better acoustic performance characteristics if this sandwich design was modified. Thus, the crystal elements and metal plates in the sandwich transducer were replaced by a stack of ceramic elements and end masses, respectively. This evolution produced the longitudinal piston vibrator shown in Fig. 19 [57]. In this transducer, the tailmass is an inertial mass while the stack of barium titanate rings causes the headmass to vibrate and consequently radiate into the water.

Several other perovskite and oxide ceramic compositions investigated during the early 1950s form the basic constituents of modern piezoelectric ceramics. These compositions included lead

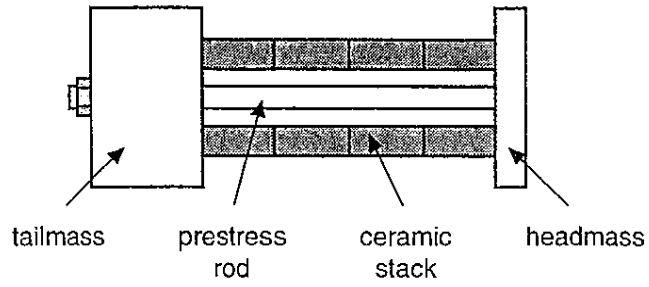


Figure 19: Ceramic driven piston vibrator.

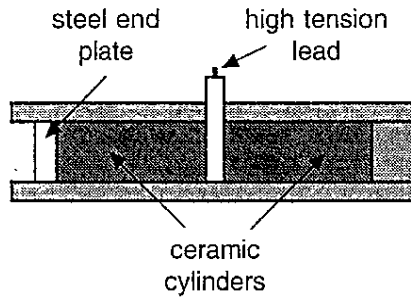


Figure 20: Piezoelectric ceramic ignition unit.

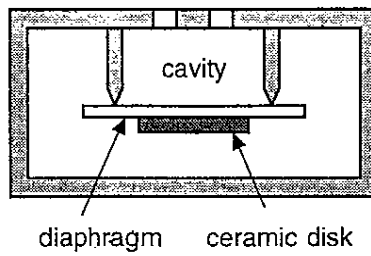


Figure 21: Piezoelectric ceramic buzzer.

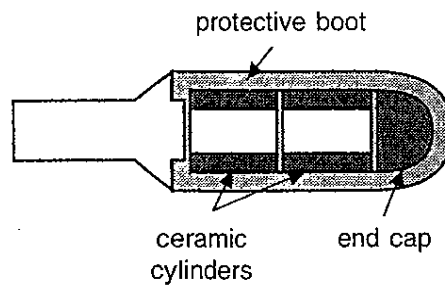


Figure 22: Piezoelectric ceramic hydrophone.

titanate (PbTiO_3) in 1950 [58, 59], lead zirconate (PbZrO_3) in 1950 [59, 60, 61], lead metaniobate (PbNb_2O_6) in 1952 [62], and in lead zirconate titanate [$\text{Pb}(\text{Zr}, \text{Ti})\text{O}_3$] in 1952 [63, 64, 65]. Lead zirconate titanate became the dominant piezoelectric ceramic material for transducers primarily due to its high coupling coefficient. Typical coupling coefficients for barium titanate and lead zirconate titanate piezoceramics are given in Table 4, along with the coupling coefficients of X cut quartz, 45°X cut Rochelle salt, and 45°Z cut ADP crystals for comparative purposes [66].

Table 4. Coupling Coefficients of Piezoelectric Materials

Piezoelectric Material	Coupling Coefficient ^a
X cut quartz	0.10
45°Z cut ADP	0.29
45°X cut Rochelle salt	0.67
barium titanate	0.46
lead zirconate titanate	0.65

^aFrom Ref. 66

The material properties for five piezoelectric ceramic compositions manufactured by the BM Hi-Tech Division of Sensor Technology Limited are listed in Table 5 [67]. The densities and key compliance, piezoelectric, and permittivity constants are given for modified lead titanate (BM300^1), low-loss lead zirconate titanate (BM400^1), high-coupling lead zirconate titanate (BM500^1), low-loss high-power lead zirconate titanate (BM800^1), and modified lead metaniobate (BM900^1). Additional piezoelectric ceramic materials and their properties can be found in Ref. 67, Jaffe et al. [42], Wilson [68], and Berlincourt et al. [69].

Transducers made from lead zirconate titanate ceramic elements can be used to generate sparks in a high-voltage spark gap. This effect has led to a number of applications that require the ignition of combustible gases. Some of these igniter applications have been summarized by Berlincourt [70]. A simple piezoelectric ignition system incorporating two ceramic cylinders, as shown in Fig. 20. When subjected to static or dynamic loads via the end plate, the ceramic cylinders can generate voltages as high as 20,000 volts in the high tension lead; sufficient to produce a spark in a spark gap. The spark gap is normally connected in parallel. Piezoelectric igniters have been used in gas-run domestic appliances, lawn mowers, welding equipment, and pocket lighters.

Lead zirconate titanate flexural transducers have a broad range of applications involving the generation and reception of sound. Examples include microphones, headphones, loudspeakers, and buzzers. The latter device, the piezoelectric buzzer, has been used as a compact alarm in wrist-watches, clocks, and calculators. A simple ceramic buzzer is described by Tanaka [56] and a sketch is shown in Fig. 21. A piezoelectric ceramic disc bonded to a thin metal diaphragm forms a bimorph that vibrates at resonance with high efficiency. Piezoelectric buzzers are highly reliable and have long lifetimes.

Table 5: Properties of Piezoelectric Ceramics

Material Constants		BM300 ^a	BM400 ^a	BM500 ^a	BM800 ^a	BM900 ^a
Density	(kg/m ³)					
ρ		6700	7600	7650	7600	6000
Compliance	(10 ⁻¹² m ² /N)					
s_{11}^E		7.2	12.5	15.5	11.0	27.5
s_{33}^E		9.0	15.0	19.0	13.5	21.0
Piezoelectric	(10 ⁻¹² C/N)					
d_{33}		65	285	365	220	75
d_{31}		- 3.0	-115	- 160	- 80	- 10
Permittivity	(10 ⁻¹⁰ F/m)					
ϵ_{33}^T		18	120	155	89	27

^a Trademarks of Sensor Technology Limited (See Ref. 67)

Piezoelectric lead zirconate titanate ceramics are also used as the active elements in hydrophones and projectors that receive and generate underwater sound, respectively. A typical hydrophone design is shown in Fig. 22. In this design there are two piezoelectric ceramic cylinders that generate electrical signals in response to incident sound waves. The end cap enhances the sensitivity of the hydrophone and the polymer boot protects the active elements from the harsh seawater environment. Detailed discussions on general hydrophone design and performance can be found in Stansfield [71] and descriptions of standard hydrophones for acoustic calibration measurements are given by Bobber [72].

The majority of underwater sonar projectors commercially available today use piezoelectric lead zirconate titanate ceramics as the active elements and operate at their resonance frequencies, where they are efficient radiators. Free-flooded ceramic ring projectors, like the segmented ring shown in Fig. 23, are ideal for high power operation at great ocean depths. The ring is usually fabricated from tangentially poled ceramic segments that are bonded together at the electrodes, with adjacent segments having opposite polarity. Both ring and cavity modes can be excited in this design. A discussion of the ring transducer is given by Camp [66].

Flexural mode projectors, such as the trilaminar disc and the flextensional transducer are often used as low frequency sound sources since they can be designed for high power performance at low frequencies, and at the same time are small and light enough for ease of handling. This is not the case for the longitudinal vibrator like the one shown in Fig. 19, which necessarily becomes large and unwieldy when designed for low frequency operation; a problem that is discussed in detail by Woollett [73]. The trilaminar disc shown in Fig. 24 is excited into flexure by two ceramic discs attached to the top and bottom surfaces of a central aluminum disc. When the ceramic elements are subjected to an electric field, one elongates while the other contracts, causing the entire trilaminar structure to vibrate in flexure. Further details can be found in Camp [66].

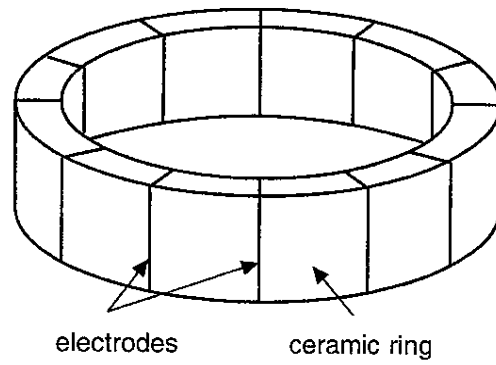


Figure 23: Segmented ceramic ring projector.

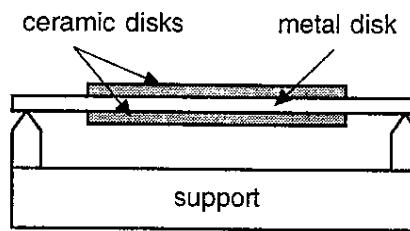


Figure 24: Ceramic trilaminar disk projector.

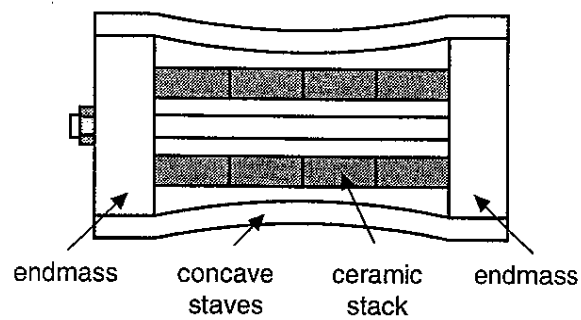


Figure 25: Ceramic barrel-stave flextensional projector.

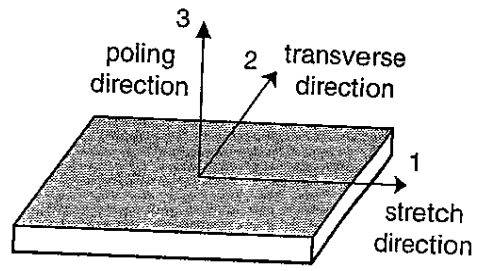


Figure 26: Piezoelectric PVDF film.

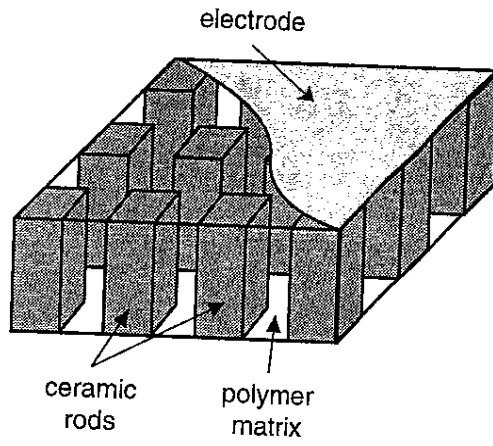


Figure 27: Piezoelectric 1-3 composite.

As mentioned earlier, the longitudinal vibrator in Fig. 19 evolved from the quartz-steel sandwich transducer shown in Fig. 11 with the discovery and development of piezoelectric ceramics. Along with this evolution came a reduction in resonance frequency. The next evolutionary step was driven by the need to reduce the frequency further in order to extend the effective range of sonar systems. Thus, various types of flexensional transducers were built, including the barrel-stave flexensional projector shown in Fig. 25. In this projector, an electric field is applied to the ceramic stack, which in turn causes the stiff steel end masses to vibrate along the longitudinal axis of the transducer. Through mechanical lever action, the end masses force a set of concave aluminum staves to vibrate in flexure and consequently radiate low frequency sound into the water. Details on the construction and performance of barrel-stave flexensional projectors and other modern flexensional designs can be found in Jones [74], Jones and Reithmeier [75], Jones et al. [76], and Jones and Lindberg [77].

3.3 Piezoelectric Polymers

The vinylidene fluoride monomer $\text{CH}_2 - \text{CF}_2$ has been known for over ninety years and forms the basic building block of the semicrystalline polymer polyvinylidene fluoride (PVDF) [78]. This long chain polymer was discovered to be highly piezoelectric in 1969 by Kawai [79] and rapid development and commercialization followed shortly afterward. PVDF is manufactured in sheet form starting with nonpolar α -phase film extruded from the melt. The extruded film material is stretched uniaxially, a process that rotates the long chain molecules and produces the polar β -phase needed for high piezoelectric activity. Finally, the randomly directed dipoles associated with the stretched β -phase film are reoriented by applying a poling field in a direction normal to the plane of the film. The resulting piezoelectric PVDF film has orthotropic symmetry with the principal axes shown in Fig. 26. Further details on the structure and production of PVDF are given by Sessler [80], Lovinger [81], Bloomfield and Marcus [82], and Davis [83].

Polyvinylidene fluoride has also been combined with other polymers in an attempt to synthesize copolymer materials with strong piezoelectric activities [81]. One such material is the piezoelectric copolymer polyvinylidene fluoride-trifluoroethylene, abbreviated here as $\text{VF}_2 - \text{VF}_3$. This copolymer can be used in underwater hydrophone applications, as discussed below in connection with PVDF.

For some applications, PVDF has attractive advantages over piezoelectric ceramics. For example, since PVDF film is flexible and lightweight, it has been used for audio transducers such as microphones, tone generators, headphones, and high-frequency loudspeakers [84]. One application of note for PVDF film transducers is the musical instrument pick-up. Small polymer strips can be attached to a variety of instruments from guitars and pianos to woodwinds and drums with good sound reproduction characteristics [85]. Other application areas for PVDF devices include medical transducers [86], electromechanical transducers [87], and pyroelectric and optical devices [88, 89].

Piezoelectric PVDF and its copolymer $\text{VF}_2 - \text{VF}_3$ have low mechanical quality factors, high hydrostatic mode responses, and are well matched to the acoustic impedance of water, making them useful materials for sonar hydrophones. Since the open circuit voltage sensitivity (m_o) and the material figure of merit (FOM_m) of a candidate material for hydrostatic mode hydrophones are given by Powers [90] as

$$m_o = g_h t \quad (40)$$

and

$$FOM_m = \frac{g_h d_h}{\tan \delta} \quad (41)$$

respectively, where g_h is the hydrostatic piezoelectric voltage constant, d_h is the hydrostatic piezoelectric strain constant, $\tan \delta$ is the electrical dissipation factor, and t is the thickness of the piezoelectric material, then it is possible to use these quantities to compare various materials for hydrostatic mode hydrophones. The hydrostatic mode piezoelectric properties of PVDF and $VF_2 - VF_3$ are given in Table 6, along with other piezoelectric materials of interest. Note that these two piezoelectric polymers have better g_h constants and material figures of merit than the piezoelectric ceramics and composites.

Table 6: Hydrostatic Properties of Piezoelectric Hydrophone Materials

Material	g_h (mV m/N)	d_h (pC/N)	FOM_m (pm ² /N)
Ceramics^a			
BM300	31	59	90
BM500	2	45	6
Polymers^b			
PVDF	152	14	160
$VF_2 - VF_3$	148	15	200
Composites^b			
1-3 PT / Epoxy ^c	71	40	140
0-3 PR-307 ^d	111	44	98

^aFrom Ref. 67

^bFrom Ref. 94

^cPT is an abbreviation for lead titanate

^dTrademark of NGK Spark Plugs Corporation

3.4 Piezoelectric Composites

Multi-phase piezoelectric composites have been developed in order to take advantage of both the piezoelectric activity of monolithic ceramics and the low mass density of non-piezoelectric polymeric materials. Like the piezoelectric polymers discussed previously, these composites can be used in hydrostatic mode hydrophone applications and as a result, have been tailored to maximize the hydrostatic properties found in Eqs. (40) and (41).

A number of macroscopic composite configurations consisting of phases of various ceramic and polymer materials are possible. Some of these are described by Safari et al. [91] and Hanish [92]. These configurations are most easily described by the connectivity nomenclature that

is employed by most researchers in the field. In the case of a two phase ceramic/polymer composite, a number is assigned to each phase representing the number of directions (dimensions) in an orthogonal axis coordinate scheme that each phase is self-connected. The active ceramic material number is written first followed by the passive polymer number. For example, the 1-3 composite shown in Fig. 27. consists of piezoelectric ceramic rods self-connected in one direction and embedded in a polymer matrix that is self-connected in all three directions. Another connectivity of interest for hydrophone applications is the 0-3 composite in which non-contiguous particulates of piezoelectric ceramic are embedded in a polymer matrix. The hydrostatic material properties of typical 1-3 and 0-3 composites are given in Table 6.

The application of piezoelectric composite materials to hydrophones is discussed in Garner et al. [93], Ting [94], Smith [95], Hayward et al. [96], and Zhang et al. [97]. The application of piezoelectric composites for underwater sound control is discussed by Gentilman et al. [98].

3.5 High Strain Materials

New high strain materials have been developed in recent years for actuators and high power sonar transducers. The traditional piezoelectric lead zirconate titanate ceramic compositions used in these applications are being challenged by magnetostrictive alloys and electrostrictive ceramics. This situation has prompted transducer researchers to investigate the electrical and mechanical stress limitations of piezoelectric ceramics in order to assess the improvements promised by the new high strain materials [99].

High strain materials include the rare earth-based magnetostrictive alloy terbium dysprosium iron ($Tb_{0.3}Dy_{0.7}Fe_{1.93}$), the cryogenic temperature (77 K) rare earth magnetostrictive alloy terbium dysprosium ($Tb_{0.6}Dy_{0.4}$), and the electrostrictive relaxor ceramic lead magnesium niobate-lead titanate PMN-PT. To operate as high power drivers for sonar projectors, these materials are electrically excited by an alternating waveform superposed on top of a static biasing field. Alternatively, the magnetostrictive alloys can be biased using permanent magnets. The application of high strain terbium dysprosium iron, terbium dysprosium, and lead magnesium niobate-lead titanate to high power transducers is discussed by Moffett and Clay [100], Clark et al. [101], and Pilgrim et al. [102], respectively.

Quasi-static room temperature properties of lanthanum doped PMN-PT were presented by McLaughlin et al. [103] at the 1996 ONR Transducer Materials and Transducers Workshop, sponsored by the Office of Naval Research and the Materials Research Laboratory at The Pennsylvania State University. The properties of interest for high power sonar transducers included the Young's modulus (Y_{33}^E), the piezoelectric d_{33} constant, the coupling constant k_{33} , and the energy density (ϵ) given by

$$\epsilon = \frac{1}{2} Y_{33}^E \left(\frac{S_{p-p}}{2} \right)^2 \quad (42)$$

where S_{p-p} is the peak-to-peak strain of the material. These properties were compared to those of lead zirconate titanate ceramic and the terbium dysprosium iron alloy Terfenol-D [104]. Note that the corresponding properties for the magnetostrictive alloy are Y_{33}^H and the piezomagnetic d_{33} constant. The reported properties are given in Table 7. By taking 10 times the logarithm of the energy density ratio with the ceramic energy density as the reference value, the predicted

improvement in power levels of PMN-PT and Terfenol-D sonar projectors over their ceramic counterparts, are 9.5 and 9.3 dB, respectively. The magnitude of these improvements are being realized in experimental transducer designs today and will continue to have an impact on the performance of future high power sonar systems.

Table 7: Comparison of the Properties of High Strain Materials

Quantity	PZT-8 ^a	PMN-PT ^b	Terfenol-D ^c
Field Limit $p_p/2$	560 kV/m	830 kV/m	64 kA/m
Prestress	0 MPa	55.2 MPa	40.4 MPa
Y_{33}^E (Y_{33}^H)	74 GPa	88 GPa	29 GPa
d_{33}	230 pm/V	410 pm/V	9.1 nm/A
k_{33}	0.64	0.37	0.67
$S_{p-p}/2$	130 ppm	340 ppm	580 ppm
Energy Density	580 J/m ³	5200 J/m ³	4900 J/m ³
Power Level (Relative to PZT-8)	0 dB	9.5 dB	9.3 dB

^a Trademark of Vernitron (See Ref. 103)

^b From Ref. 103

^c From Ref. 104