MEASUREMENT
SPECIALTIES

Piezo Film Sensors

Technical Manual

Internet Version

Part 1 of 18

INTRODUCTION

Transducer materials convert one form of energy into another, and are widely used in sensing applications. The tremendous growth in the use of microprocessors has propelled the demand for sensors in diverse applications. Today, **PIEZOELECTRIC POLYMER SENSORS** are among the fastest growing of the technologies within the $18 billion worldwide sensor market. Like any new technology, there have been an extraordinary number of applications where **"PIEZO FILM"** has been considered for the sensor solution. In the 20 years since the discovery of piezoelectric polymer, the technology has matured, practical applications have emerged from a long list of possibilities, and the rate of commercialization of the technology is accelerating.

These documents provide an overview of piezoelectric polymer technology and nomenclature, its properties, and sensor design considerations. It also explores a range of sensor applications that have been successfully developed in recent years.

Solving unique sensor problems is a particular strength of our group of applications engineers. We welcome the opportunity to provide assistance to you during your evaluation of piezo film sensors for your design.

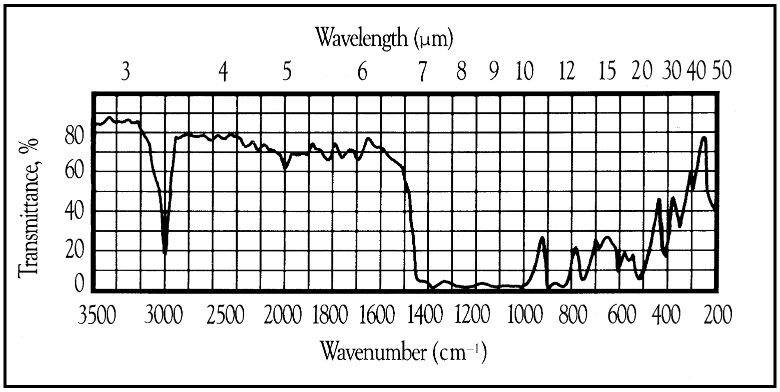
BACKGROUND

Piezoelectricity, Greek for "pressure" electricity, was discovered by the Curie brothers more than 100 years ago. They found that quartz changed its dimensions when subjected to an electrical field, and conversely, generated electrical charge when mechanically deformed. One of the first practical applications of the technology was made in the 1920's by another Frenchman, Langevin, who developed a quartz transmitter and receiver for underwater sound - the first SONAR. Before World War II, researchers discovered that certain ceramic materials could be made piezoelectric when subjected to a high polarizing voltage, a process analogous to magnetizing a ferrous material.

By the 1960's, researchers had discovered a weak piezoelectric effect in whale bone and tendon. This began an intense search for other organic materials that might exhibit piezoelectricity. In 1969, Kawai found very high piezo-activity in the polarized fluoropolymer, Polyvinylidene fluoride (PVDF). While other materials, like nylon and PVC exhibit the effect, none are as highly piezoelectric as PVDF and its copolymers.

Like some other ferroelectric materials, PVDF is also highly pyroelectric, producing electrical charge in response to a change in temperature. PVDF is strongly absorbing of infrared energy in the 7-20μm wavelengths (see Figure 1), covering the same wavelength spectrum as heat from the human body. Accordingly, PVDF makes a useful human motion sensor as well as pyroelectric sensor for more sophisticated applications like vidicon cameras for night vision and laser beam profiling sensors. Piezo film can detect body motion at up to fifty feet with a suitable Fresnel lens, and has also been employed in infrared horizon sensors in satellites.

Figure 1. Typical infrared absorption spectrum of PVDF film.



New copolymers of PVDF, developed over the last two years, have expanded the applications of piezoelectric polymer sensors. These copolymers permit use at higher temperatures (135°C) and offer desirable new sensor shapes, like cylinders and hemispheres. Thickness extremes are possible with copolymer that cannot be readily attained with PVDF. These include ultrathin (200 Å) spin-cast coatings that open the possibilities of new sensor-on-silicon applications, and cylinders with wall thicknesses in excess of 1200μm for sonar.

PIEZOELECTRIC FILM PROPERTIES

Piezo film is a flexible, lightweight, tough plastic film available in a wide variety of thicknesses and large areas. Its properties as a transducer include:

- Wide frequency range—0.001 Hz to 10^9 Hz.
- Vast dynamic range (10^{-8} to 10^6 psi or μ torr to Mbar).
- Low acoustic impedance—close match to water, human tissue and adhesive systems.
- High elastic compliance
- High voltage output—10 times higher than piezo ceramics for the same force input.
- High dielectric strength—withstanding strong fields (75V/μm) where most piezo ceramics depolarize.
- High mechanical strength and impact resistance (10^9—10^{10} Pascal modulus).
- High stability—resisting moisture (<0.02% moisture absorption), most chemicals, oxidants, and intense ultraviolet and nuclear radiation.
- Can be fabricated into unusual designs.
- Can be glued with commercial adhesives.

One major advantage of piezo film is its low acoustic impedance which is closer to that of water, human tissue and other organic materials, than piezo ceramics. For example, the acoustic impedance ($Z_O = \rho\, \upsilon$) of piezo film is only 2.6 times that of water, whereas piezo ceramics are typically 11 times greater. A close impedance match permits more efficient transduction of acoustic signals in water and tissue.

Piezo film does have some limitations for certain applications. It makes a relatively weak electromechanical transmitter when compared to ceramics, particularly at resonance and in low frequency applications. The copolymer film has maximum operating/storage temperatures as high as 135°C. Also, if the electrodes on the film are exposed, the sensor can be sensitive to electromagnetic radiation. Good shielding techniques are available for high EMI/RFI environments.

Table 1 lists typical properties of Piezo Film. Table 2 provides a comparison of the piezoelectric properties of PVDF polymer and two popular piezoelectric ceramic materials.

The film's optical transmission characteristics are shown in Figure 1. The strong absorption of infrared energy at 7-20μm wavelengths makes piezo film ideal for intrusion detection and energy management devices.

PVDF film is typically thin, flexible, has low density and excellent sensitivity, yet piezo film is mechanically tough. The compliance of piezo film is 10 times greater than the compliance of ceramics. When extruded into thin film, piezoelectric polymers can be directly attached to a structure without disturbing its mechanical motion. Piezo film is well suited to strain sensing applications requiring very wide bandwidth and high sensitivity. As an actuator, the polymer's low acoustic impedance permits the efficient transfer of energy into air and other gases.

Table 1. Typical properties of piezo film

Symbol	Parameter	PVDF	Copolymer	Units
d_{31}	Piezo Strain Constant	23	11	10^{-12} $\frac{m/m}{V/m}$ *or* $\frac{C/m^2}{N/m^2}$
d_{33}		-33	-38	
g_{31}	Piezo Stress constant	216	162	10^{-3} $\frac{V/m}{N/m^2}$ or $\frac{m/m}{C/m^2}$
g_{33}		-330	-542	
k_{31}	Electromechanical Coupling Factor	12%	20%	
k_t		14%	25-29%	
C	Capacitance	380 for 28μm	68 for 100μm	pF/cm^{2,} @ 1kHz
Y	Young's Modulus	2-4	3-5	10^9 N/m^2
V_0	Speed of Sound stretch:	1.5	2.3	10^3 m/s
	thickness:	2.2	2.4	
p	Pyroelectric Coefficient	30	40	10^{-6} C/m^2 °K
ε	Permittivity	106-113	65-75	10^{-12} F/m
$\varepsilon/\varepsilon_0$	Relative Permittivity	12-13	7-8	
ρ_m	Mass Density	1.78	1.82	10^3kg/m
ρ_e	Volume Resistivity	$>10^{13}$	$>10^{14}$	Ohm meters
$R_\square$	Surface Metallization Resistivity	2.0	2.0	Ohms/square for CuNi
$R_\square$		0.1	0.1	Ohms/square for Ag Ink
tan δ_e	Loss Tangent	0.02	0.015	@ 1kHz
	Yield Strength	45-55	20-30	10^6 N/m^2 (stretch axis)
	Temperature Range	-40 to 80	-40 to 115...145	°C
	Water Absorption	<0.02	<0.02	% H_2O
	Maximum Operating Voltage	750 (30)	750 (30)	V/mil(V/μm), DC, @ 25°C
	Breakdown Voltage	2000 (80)	2000 (80)	V/mil(V/μm), DC, @ 25°C

Table 2. Comparison of piezoelectric materials

Property	Units	PVDF Film	PZT	$BaTi0_3$
Density	10^3kg/m3	1.78	7.5	5.7
Relative Permittivity	$\varepsilon/\varepsilon_0$	12	1,200	1,700
d_{31} Constant	(10^{-12})C/N	23	110	78
g_{31} Constant	(10^{-3})Vm/N	216	10	5
k_{31} Constant	% at 1 kHz	12	30	21
Acoustic Impedance	(10^6)kg/m^2-sec.	2.7	30	30

OPERATING PROPERTIES FOR A TYPICAL PIEZO FILM ELEMENT

The DT1 element is a standard MSI piezo film configuration consisting of a 12x30 mm active area printed with silver ink electrodes on both surfaces of a 15x40 mm die-cut piezo polymer substrate.

1. **Electro-Mechanical Conversion**
   (1 direction) 25 x 10^{-12}m/V, 700 x 10^{-6}N/V
   (3 direction) 33 x 10^{-12}m/V

2. **Mechano-Electrical Conversion**
   (1 direction) 12 x 10^{-3}Vμ/ε, 400 x 10^{-3}V/μm 14.4V/N
   (3 direction) 13 x 10^{-3}V/N

3. **Pyro-Electrical Conversion**
   8V/°K (@ 25°C)

4. **Capacitance**
   1.36 x 10^{-9}F; Dissipation Factor 0.018 @ 10 KHz Impedance @ 10 KHz 12 KΩ

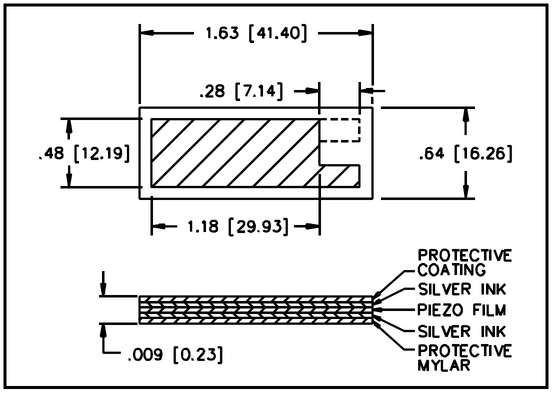
5. **Maximum Operating Voltage**
   DC: 280 V (yields 7 μm displacement in 1 direction)
   AC: 840 V (yields 21 μm displacement in 1 direction)

6. **Maximum Applied Force (at break, 1 direction)**
   6-9 kgF (yields voltage output of 830 to 1275 V)

Electrical to Mechanical Conversion

Large displacements or forces are not generally available from Piezo Film. This becomes apparent when designing loudspeaker elements for instance, as low frequency performance (below 500Hz) tends to be very limited. Even a large sheet of film is unable to create high amplitude pressure pulses as low audio frequencies. This does not apply, however, to low to high frequency ultrasonic frequencies, as seen in current designs for ultrasound air ranging transducers (40-50 kHz) and in medical ultrasonic imaging applications.

Figure 4. DT1 Element



For air ranging ultrasound, the piezo film element height controls vertical beam angle and the curvature and width of the transducer controls horizontal beam pattern. Piezo film air ranging transducers can provide up to 360° field of view, ranging object from a few centimeters to several meters with high resolution.

Bimorph configurations (like a bimetal strip) allow the small differential displacement of two reverse-connected elements to be translated into substantial flexural motion. Small fans or optical deflectors can thus be created. Such devices consume very little real power (being capacitive in nature). Large devices may be difficult to drive due to high capacitance, especially when transformers are used to step up the drive voltage. Good amplifier design is important.

Although the forces involved are small, the film can be used to excite other mechanical structures over a very wide frequency range. If another element of film is used to receive the induced vibration, the system can possess a very high dynamic range, even though the overall "insertion loss" due to the film is about -66 dB typically for a structure at resonance. If sufficient gain is applied between these elements, the structure will self-oscillate at its natural frequency, as in the "singing technology" exploited by MSI to fabricate pressure, load and fluid level sensors. For these resonant mechanical systems, high voltage drive is not required. The amplifier circuit may function adequately from a normal dual rail op-amp supply, or even from a single 9 volt battery. For analysis purposes, even lower applied voltages, e.g., the noise source of a spectrum analyzer at 70 mVrms, are sufficient to insert the mechanical energy into a structure when Piezo Film is also used to monitor the result.

Mechanical to Electrical Conversion

The sensitivity of Piezo Film as a receiver of mechanical work input is awesome. In its simplest mode the film behaves like a dynamic strain gauge except that it requires no external power source and generates signals greater than those from strain gauges *after* amplification. Frequency response is thus free from any limitations imposed by the need for high gains and will extend up to the wavelength limit of the given transducer.

The extreme sensitivity is largely due to the format of the piezo film material. The low thickness of the film makes in turn a very small cross-sectional area and thus relatively small longitudinal forces create very large stresses within the material. It is easy to exploit this aspect to enhance the sensitivity parallel to the machine axis. If a laminated element of film (for example an LDT1-028K) is placed between two layers of compliant material then any compressive forces are converted into much larger longitudinal extensive forces. In fact, this effect tends to predominate in most circumstances since most substances are compliant to some extent and the ratio of effective sensitivity in the 1 vs 3 directions is typically 1000:1.

Piezo Film transducers may often cover a much larger area than normal strain gauges so any direct comparisons should be performed in a *uniform* strain field for meaningful results. Obviously "point"-type transducers could be used where required although the capacitance of a very small area will require consideration. The low frequency limit of operation will be defined by the greatest resistive load achievable, or by the largest capacitance load that still allows the signal to be easily detected. Operation down to fractions of Hz can be achieved using either conventional charge amplifiers or, since signal levels are relatively high, simple high impedance FET buffer circuits.

Pyro to Electrical Conversion

Kynar® Piezo Film absorbs strongly in the region of 7 to 20 μm which corresponds to well beyond both operating temperature limits of the film. It thus makes a sensitive pyroelectric detectors for, say, human body radiation. Since the pyro sensitivity is strong, care must be taken when designing

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Kynar is a registered trademark of Elf Atochem NA low (<0.01 to 1Hz) frequency mechanical sensors to avoid ambient temperature changes swamping the output with pyro-generated signal. If a very long time constant is in use, then the film will generate a voltage corresponding to the change in temperature since switch-on. Since the output will be several volts per degree C, substantial offsets may be noticed.

In general, however, most applications will have a cut-off frequency of several Hertz or more unless the pyro effect is specifically desired. Connecting a device of 1nF capacitance to an oscilloscope input, even at 10 MΩ impedance, will produce a roll off below 16 Hz. Only a rapid change in the film temperature will generate a detectable signal.

Common-mode rejection can be used to isolate either very low frequency mechanical strain from simultaneous pyro-effects or vice-versa. These techniques are quite familiar to MSI applications engineers who are available for design assistance.

Electrical Design Considerations

A useful model for the film which applies for most cases except ultrasonic applications is a strain-dependent voltage source in series with a capacitance. Thus any resistive load will form a divider network with a simple RC high-pass filter characteristic. The cut-off frequency is given by

$f_o = \frac{1}{2\pi RC}$ and the time constant $\tau = RC$. Operation below the cut-off frequency will give an output signal proportional to the rate of change of the input parameter (differentiator). Application of a constant stress will generate an initial level followed by an exponential decay of rate $\exp(RC)^{-1}$.

A capacitive load will extend the time constant but reduce the magnitude of the response. Energy is always lost when transferring charge from one capacitor to another. Large capacitive loads are useful for attenuating the very large signals arising from powerful impacts—often hundreds of volts.

When driving the film at high voltage and high frequency, the dissipation factor of the film may result in substantial energy loss in the form of heat. Also, the surface resistivity of the electrodes may become significant, especially with vacuum metallized film. Very high localized currents may be encountered. Operation within the field limits given in the Technical Manual is strongly recommended since any arcing will normally destroy the device.

Silver ink, screenprinted onto both film surfaces, has been developed to withstand high voltage and high localized currents. The silver ink metallization has been successfully used in tweeters and active vibration damping applications. The DT1 sample is electroded with the silver ink. The unmetallized border mitigates potential for arcing across the film's thickness. The offset lead attach tabs also preclude high voltage breakdown, as the conductor at each lead attach site is on one side only.

Mechanical Design Considerations

The output energy is proportional to the volume of film stressed. Film thickness may be chosen to optimize the electrical signal format or from mechanical strength considerations. Thicker films generate higher voltages but form smaller capacitors, so a laminate of thinner film with a compatible, passive material such as polyester (i.e. the LDT1-028K) may be preferable to a single thicker film. Any area of film that is not undergoing stress will act as a capacitive load on the "active" area and should be minimized if required.

Most metallizations are subject to corrosion, especially when handled. Thin conformal coatings or laminates are frequently applied to maintain surface quality. Acrylics adhesives, synthetic rubber resins, epoxies and cyano-acrylates are all frequently employed in lamination and assembly.

Some designs may use external metallic or conductive substrates as the electrodes, in which case unmetallized film may be used to good advantage. The external metal surface can be in direct contact with the unmetallized film to collect the charge, or, capacitive coupling through thin adhesive tapes or epoxy layers can be employed for ac applications. Patterning of the electrodes is especially useful for defining specific active areas on a continuous sheet and also to allow die-cutting of elements with a clear border around the cut area. Displacement (offset) of upper and lower electrode tabs at the connection point is good practice to prevent unpredictable piezo behavior in this area caused by the influence of the wire terminations. This also allows low cost penetrative lead-attach methods to be used (crimps or eyelets).

Joint Electrical and Mechanical Design Considerations

The capacitive nature of Piezo Film devices implies that they are susceptible to Electro Magnetic Interference. This becomes increasingly more important as the output signal level drops. EMI can be ignored where the output is high or when the film is being driven in a non-critical environment. A.C. mains interference may become a problem with unshielded devices. Another potential problem exists when one electrode element is being driven and an another is receiving the vibration signal. Care must be taken to avoid "crosstalk".

Use of MSI’s ready-made shielded elements supplied with coaxial cable eliminates these problems, but simple measures may be taken with any device to avoid interference.

Unwanted frequencies may be filtered out electronically. If the sensor is to be mounted on a conductive substrate, then this may form one half of a grounded envelope, with the outer electrode forming the other half. Lightweight shielded cable is readily available and is an alternative to twisted pair wires. Attention should be paid to the point of connection itself as this is also an area of EMI vulnerability.

Durable lead attachment techniques have been fully developed by MSI, and most products are supplied with leads preattached. As indicated, some form of coaxial cable is often employed and must be interfaced to a very thin flexible material. Reinforcement at the lead attach site may be required, which can introduce some acoustic effects into the transducer if the interconnection site is free to vibrate.

Thin copper foil backed with a conductive adhesive can provide excellent but non-permanent connections to the film. An area of 1 cm^2 will give a contact resistance of a few mΩ s. Crimp-through connectors as used for flexible circuits are routinely used with offset electrode patterns, but thin films require some physical reinforcement for good results. Polyester reinforcement at the lead attach site is a common method to ruggedize the interconnection. The stiffener may lie between the crimp and the electrode with only minor degradation of contact resistance. Typical values are 150-500 mΩ. Miniature rivets, eyelets and even nuts and bolts, with washers, all combine great strength with good contact resistance at typically less than 100 mΩ. These techniques may be used to connect to cables using solder tags, or direct onto printed circuit boards.

Clamping methods, either direct to the conductive traces on the PCB or using conductive rubber, ZEBRA ® connectors, lugs and washers have all been used with success. Direct connection using silver-loaded (conductive) epoxy also works well, but requires curing time, often at elevated temperature, for best results.

As indicated earlier, other materials may form the electrodes themselves, such as conductive rubber or foam. Capacitive coupling through adhesive layers is practical under some circumstances, allowing some unusual transducer designs with apparently no lead attachment at all!

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