Semiconductor Sensors:

Ch4: Capacitive sensors-

Piezoelectric Effect

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خاصیت پیزوالکتریک

- **خاصیت پیزوالکتریک و معکوس آن**

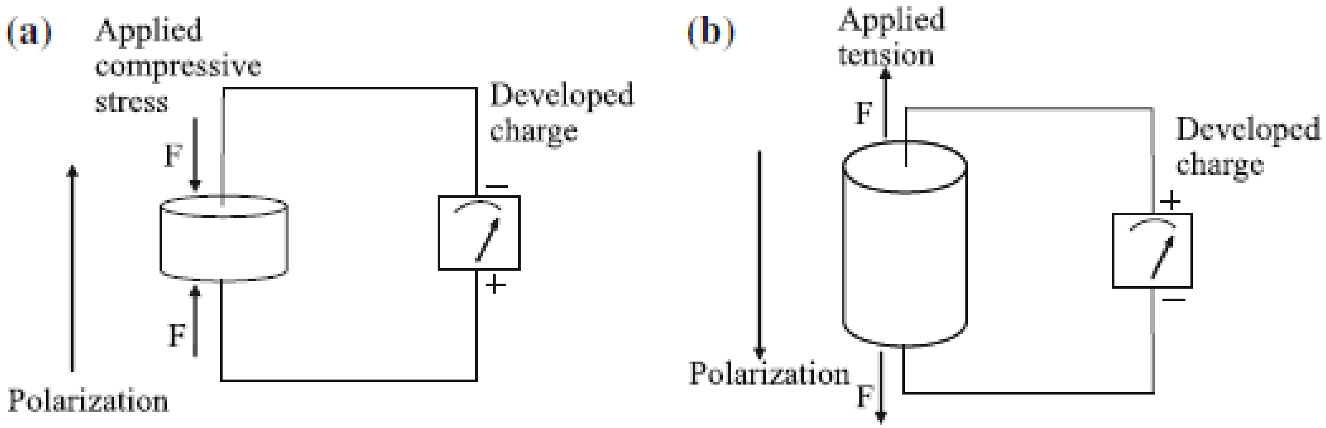


Fig. 2.1 Direct piezo-effect: a at applied compressive stress, b at applied tension

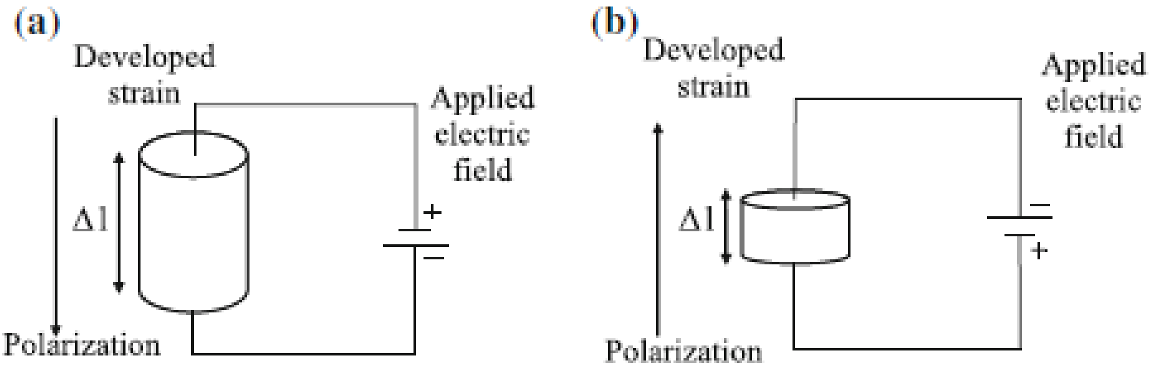


Fig. 2.2 Inverse piezo-effect at applied electric field

مواد پیزوالکتریک

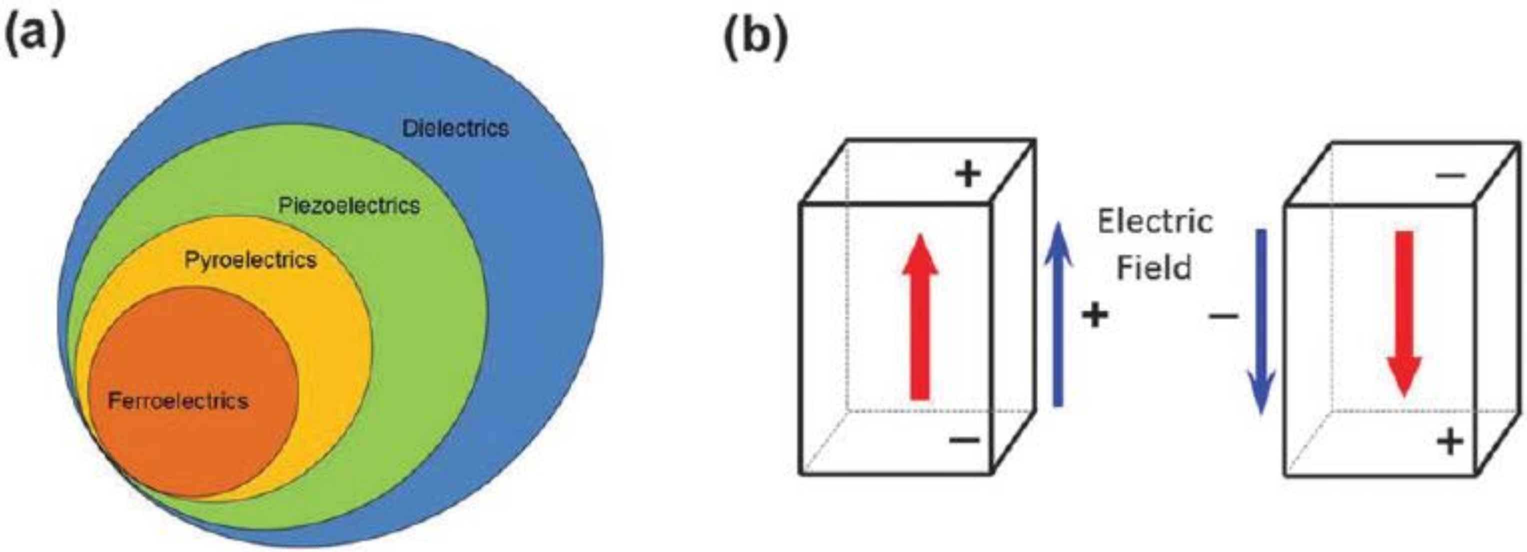
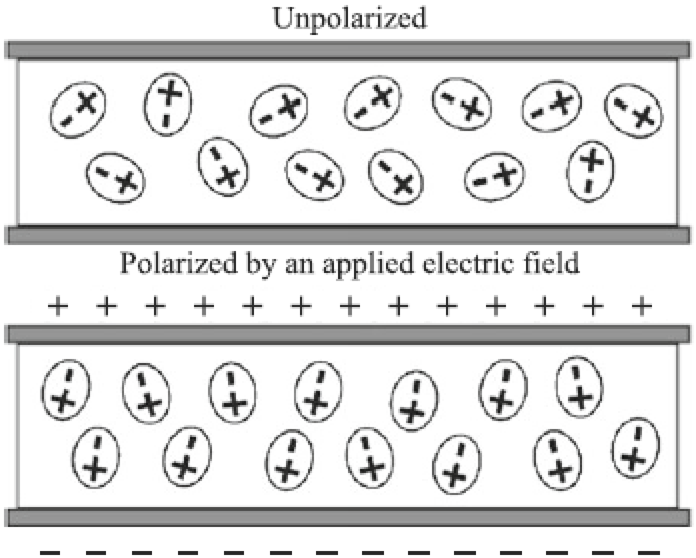
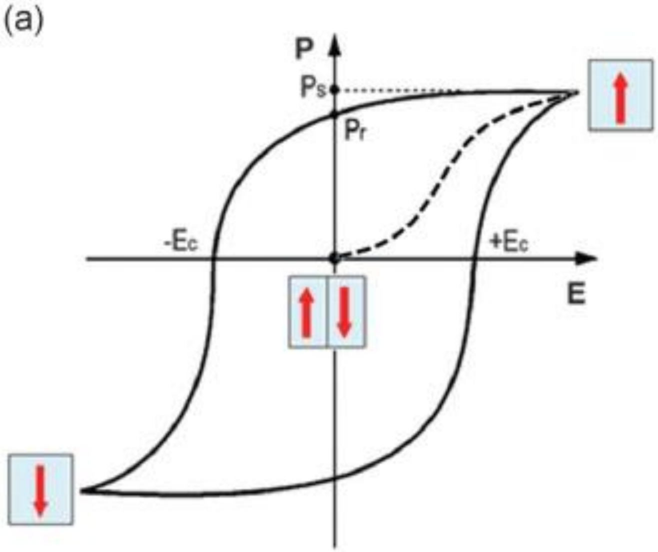


Fig. 1 (a) The relationships among dielectric, piezoelectric, pyroelectric and ferroelectric materials; (b) bipolar state of ferroelectrics that can be switched by external electric field.

Li, Jiangyu, et al. "Molecular ferroelectrics: where electronics meet biology." *Physical Chemistry Chemical* (2013)

مشخصه هیسترزیسی مواد با دوقطبی الکتریکی





Li, Jiangyu, et al. "Molecular ferroelectrics: where electronics meet biology." *Physical Chemistry Chemical* (2013)
Springer- Document- Ch2- Piezoelectric Materials

خاصیت پیزوالکتریک

- **خاصیت پیزوالکتریک ترکیب رفتارهای الکتریکی و الاستیکی ماده است:**

- The linear electrical behavior of the material:

$$\mathbf{D} = \varepsilon \, \mathbf{E} \quad \Longrightarrow \quad D_i = \varepsilon_{ij} \, E_j$$

where *D* is the electric charge density displacement (electric displacement), *ε* is permittivity (free-body dielectric constant), *E* is electric field strength, and $\nabla \cdot \mathbf{D} = 0$, $\nabla \times \mathbf{E} = \mathbf{0}$.

- Hooke's Law for linear elastic materials:

$$\boldsymbol{S} = \mathsf{s} \, \boldsymbol{T} \quad \Longrightarrow \quad S_{ij} = s_{ijkl} \, T_{kl}$$

where *S* is strain, *s* is compliance under short-circuit conditions, *T* is stress

These may be combined into so-called *coupled equations*, of which the **strain-charge form** is:

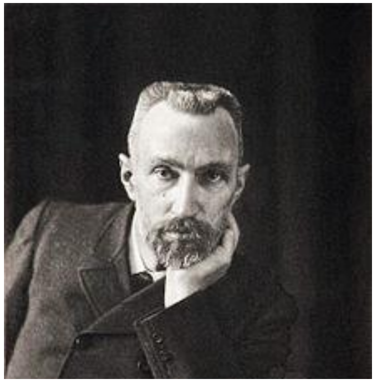
$$\begin{aligned} \boldsymbol{S} &= \mathsf{s} \, \boldsymbol{T} + \mathfrak{d}^t \, \mathbf{E} \quad &\Longrightarrow \quad S_{ij} &= s_{ijkl} \, T_{kl} + d_{kij} \, E_k \\ \mathbf{D} &= \mathfrak{d} \, \boldsymbol{T} + \varepsilon \, \mathbf{E} \quad &\Longrightarrow \quad D_i &= d_{ijk} \, T_{jk} + \varepsilon_{ij} \, E_j \, . \end{aligned}$$

In matrix form,

$$\begin{aligned} \{S\} &= \left[s^E\right] \{T\} + [d^t]\{E\} \\ \{D\} &= [d]\{T\} + \left[\varepsilon^T\right] \{E\} \, , \end{aligned}$$

where [*d*] is the matrix for the direct piezoelectric effect and [d^t] is the matrix for the converse piezoelectric effect. The superscript *E* indicates a zero, or constant, electric field; the superscript *T* indicates a zero, or constant, stress field; and the superscript t stands for transposition of a matrix.

تاریخچه پیزوالکتریک


Pierre Curie, c. 1906


Pierre and Marie Skłodowska-Curie, 1895


Piezoelectric balance presented by Pierre Curie to Lord Kelvin, Hunterian Museum, Glasgow

- 1880
  - Piezoelectric effect discovered: Brothers Pierre & Jacques Curie
- 1900s
  - First hydrothermal growth of quartz in laboratory
- 1910s
  - First application of piezoelectricity, in sonar (Rochelle salt)
  - First quartz crystal oscillator, filter

Book: W. Heywang, et al. *Piezoelectricity: evolution and future of a technology*. Vol. 114. Springer Science & Business Media, 2008.

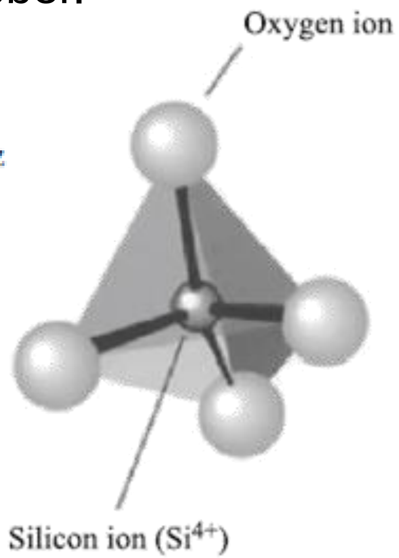
مواد پیزوالکتریک

Piezoelectric materials (PEMs) :

1- Natural PEM

Quartz (SiO_2), Rochelle salt, Topaz, Tourmaline-group minerals and some organic substances as silk, wood, enamel, dentin, bone, hair, rubber.

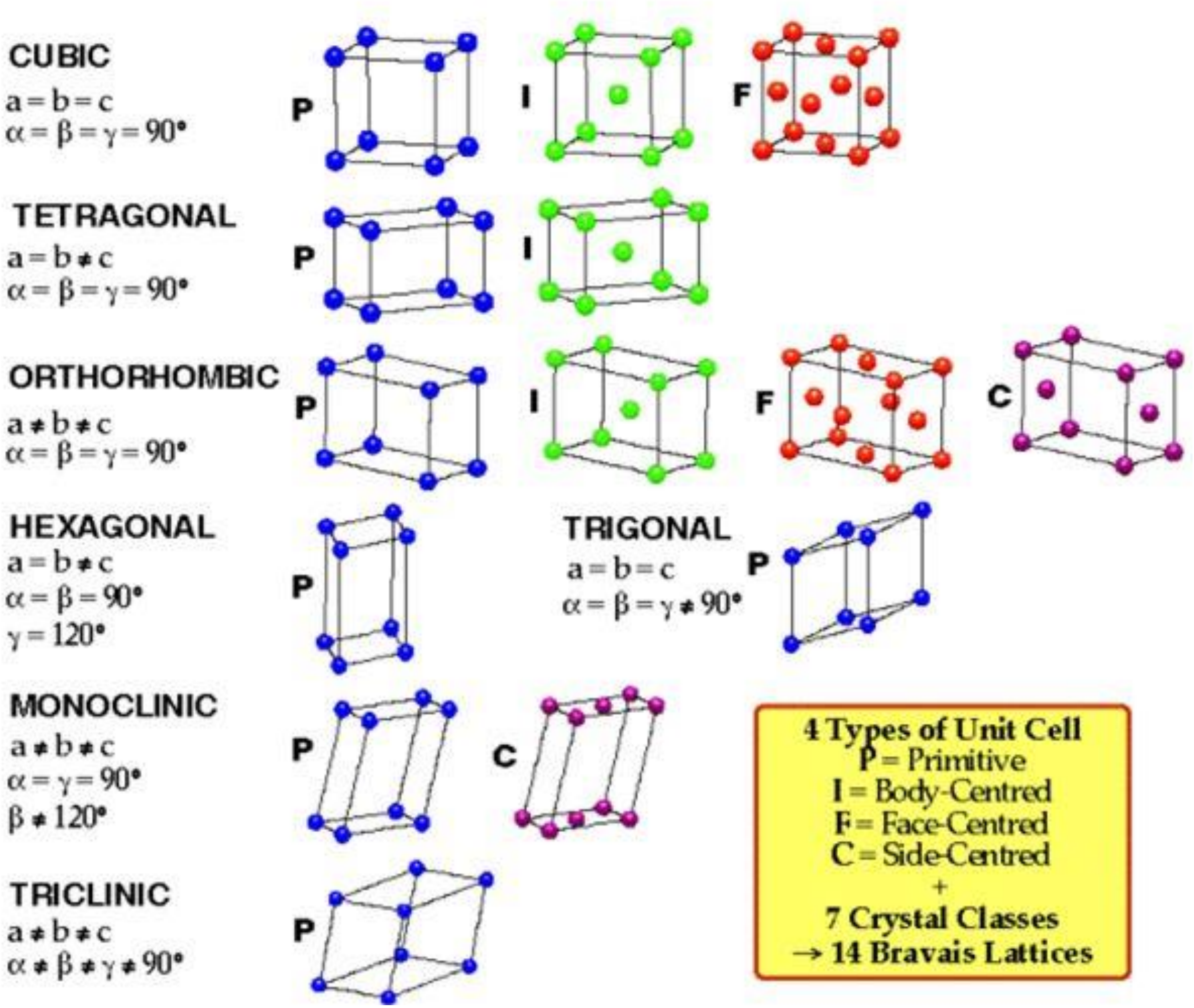
Fig. 2.3 Unit cell of quartz



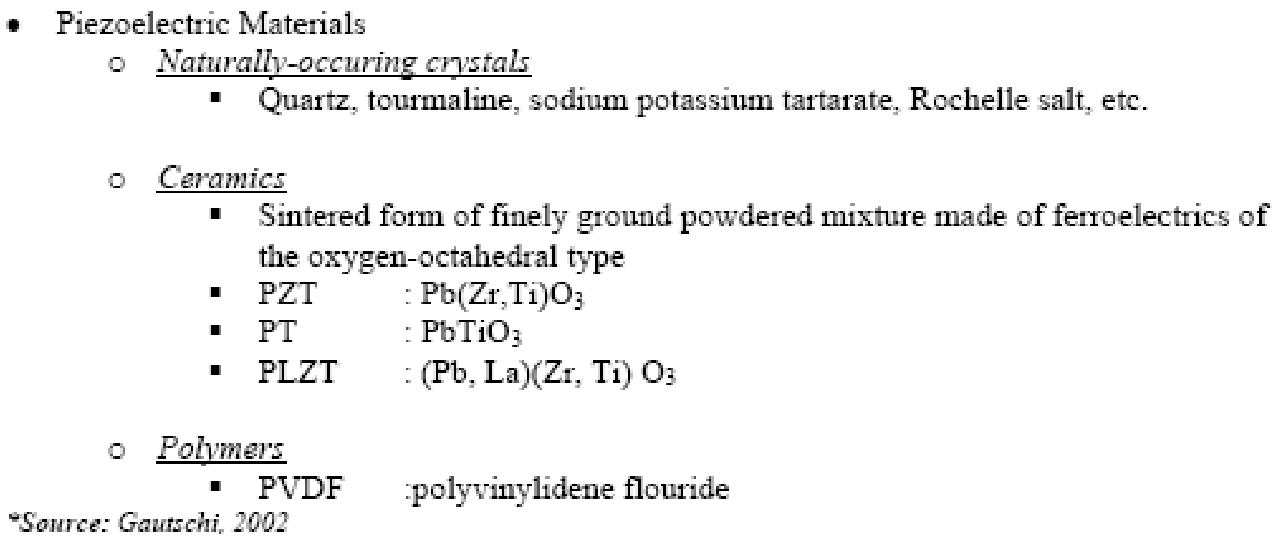
2- Man-made PEM:

There are 32 crystal classes . Only 20 of the 32 classes allow piezoelectric properties. Ten of these classes are polar with their unit cell. The remaining 10 classes are not polar, i.e. polarization appears only after applying a mechanical load.

ساختارهای کریستالی



مواد پیزوالکتریک



- Piezoelectric Materials
  - *Naturally-occuring crystals*
    - Quartz, tourmaline, sodium potassium tartarate, Rochelle salt, etc.
  - *Ceramics*
    - Sintered form of finely ground powdered mixture made of ferroelectrics of the oxygen-octahedral type
    - PZT : $Pb(Zr,Ti)O_3$
    - PT : $PbTiO_3$
    - PLZT : $(Pb, La)(Zr, Ti) O_3$
  - *Polymers*
    - PVDF :polyvinylidene flouride

**Source: Gautschi, 2002*

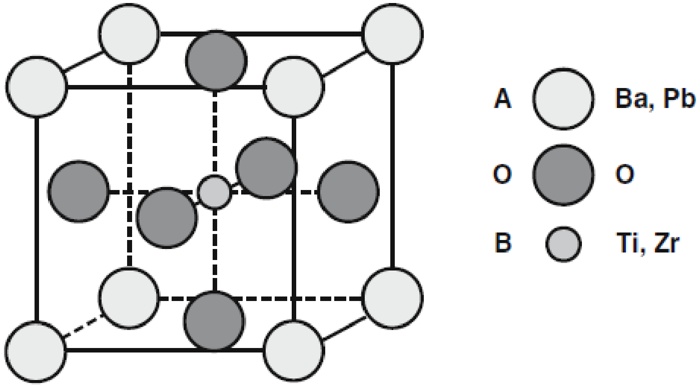


Fig. 3.1. The perovskite structure ABO_3. $BaTiO_3$ is the prototype ferroelectric that crystallizes in this structure. Other important examples are $PbTiO_3$ and $Pb(Zr_xTi_{1-x})O_3$

Book: W. Heywang, et al. *Piezoelectricity: evolution and future of a technology*. Vol. 114. Springer Science & Business Media, 2008.

مواد پیزوالکتریک – سازوکار ایجاد بار با اعمال نیرو

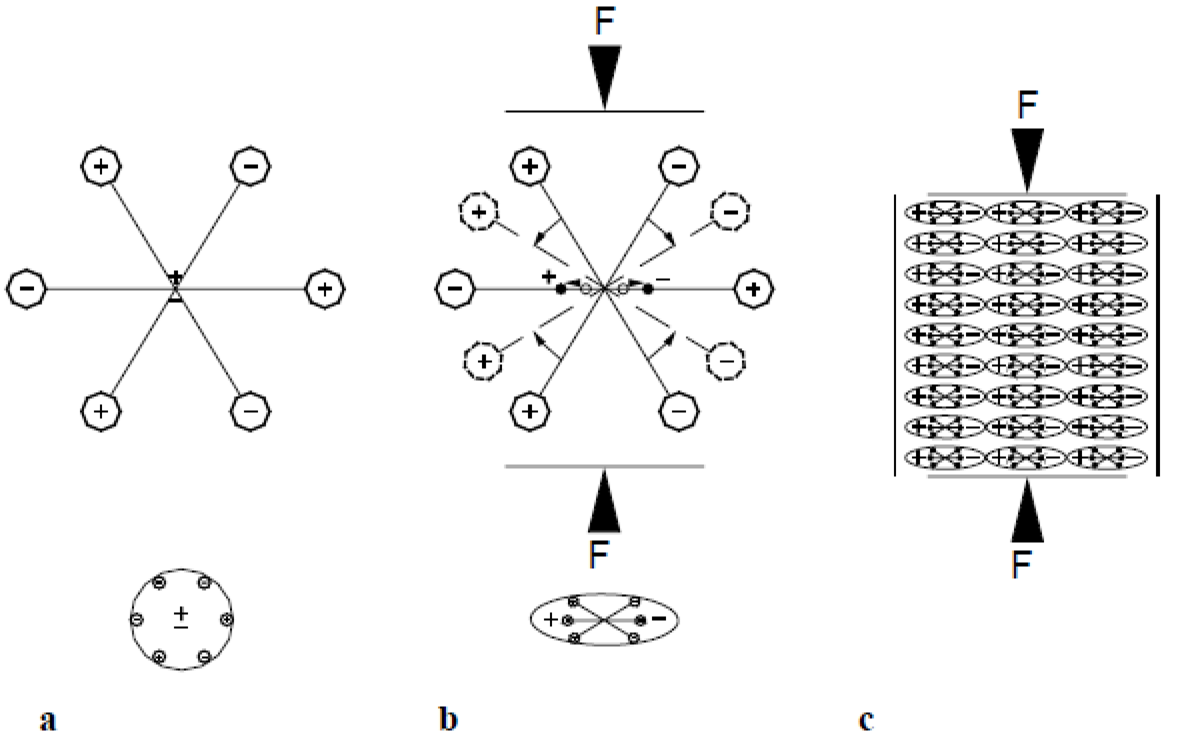


Fig. 1.1. Simple molecular model for explaining the piezoelectric effect: **a** unperturbed molecule; **b** molecule subjected to an external force, and *c* polarizing effect on the material surfaces

Arnau A. - Piezoelectric Transducers and Applications - Springer-2008.

کاربردهای خاصیت پیزوالکتریک

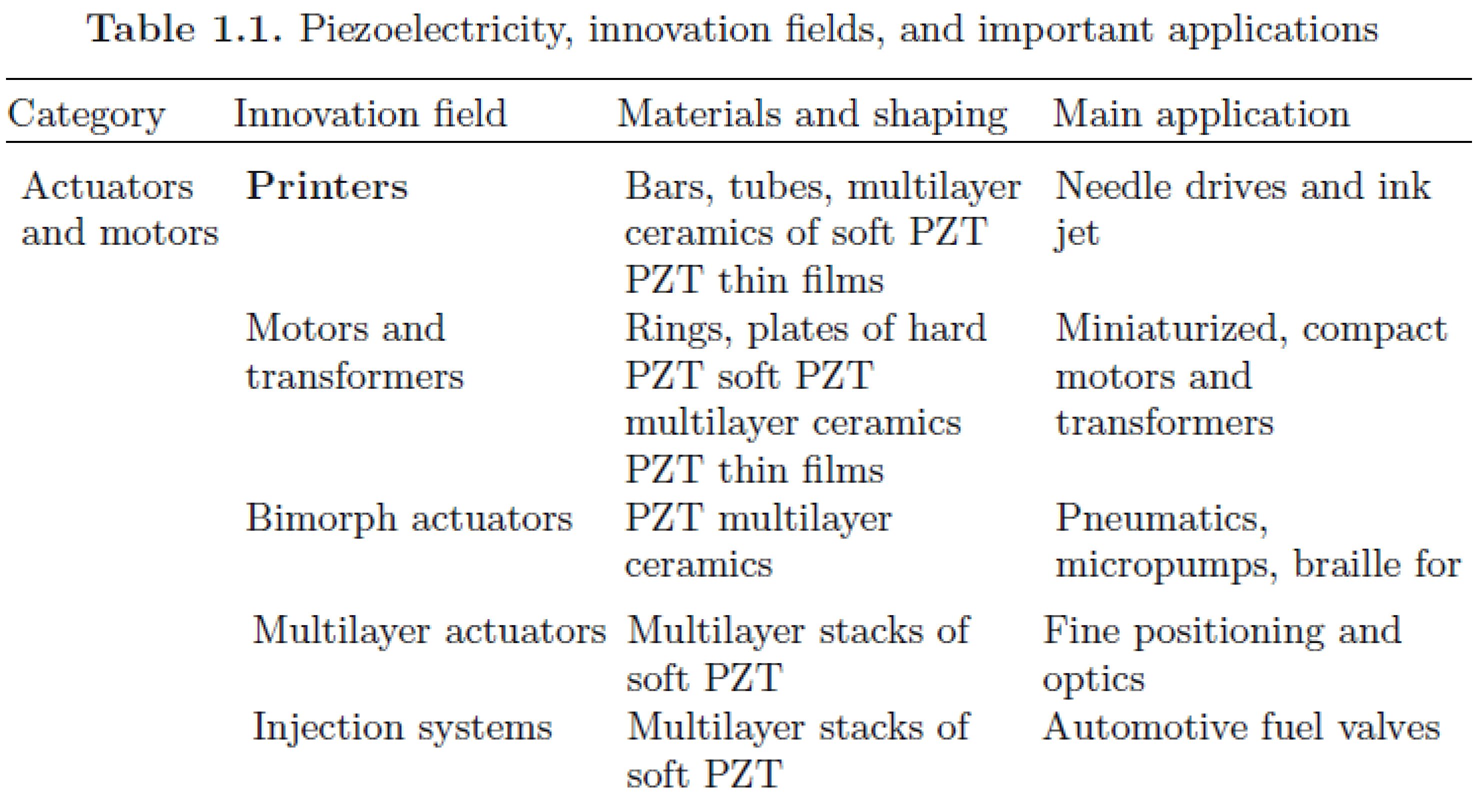


Table 1.1. Piezoelectricity, innovation fields, and important applications

Category	Innovation field	Materials and shaping	Main application
Actuators and motors	**Printers**	Bars, tubes, multilayer ceramics of soft PZT PZT thin films	Needle drives and ink jet
	Motors and transformers	Rings, plates of hard PZT soft PZT multilayer ceramics PZT thin films	Miniaturized, compact motors and transformers
	Bimorph actuators	PZT multilayer ceramics	Pneumatics, micropumps, braille for
	Multilayer actuators	Multilayer stacks of soft PZT	Fine positioning and optics
	Injection systems	Multilayer stacks of soft PZT	Automotive fuel valves

Book: W. Heywang, et al. *Piezoelectricity: evolution and future of a technology*. Vol. 114. Springer Science & Business Media, 2008.

کاربردهای خاصیت پیزوالکتریک

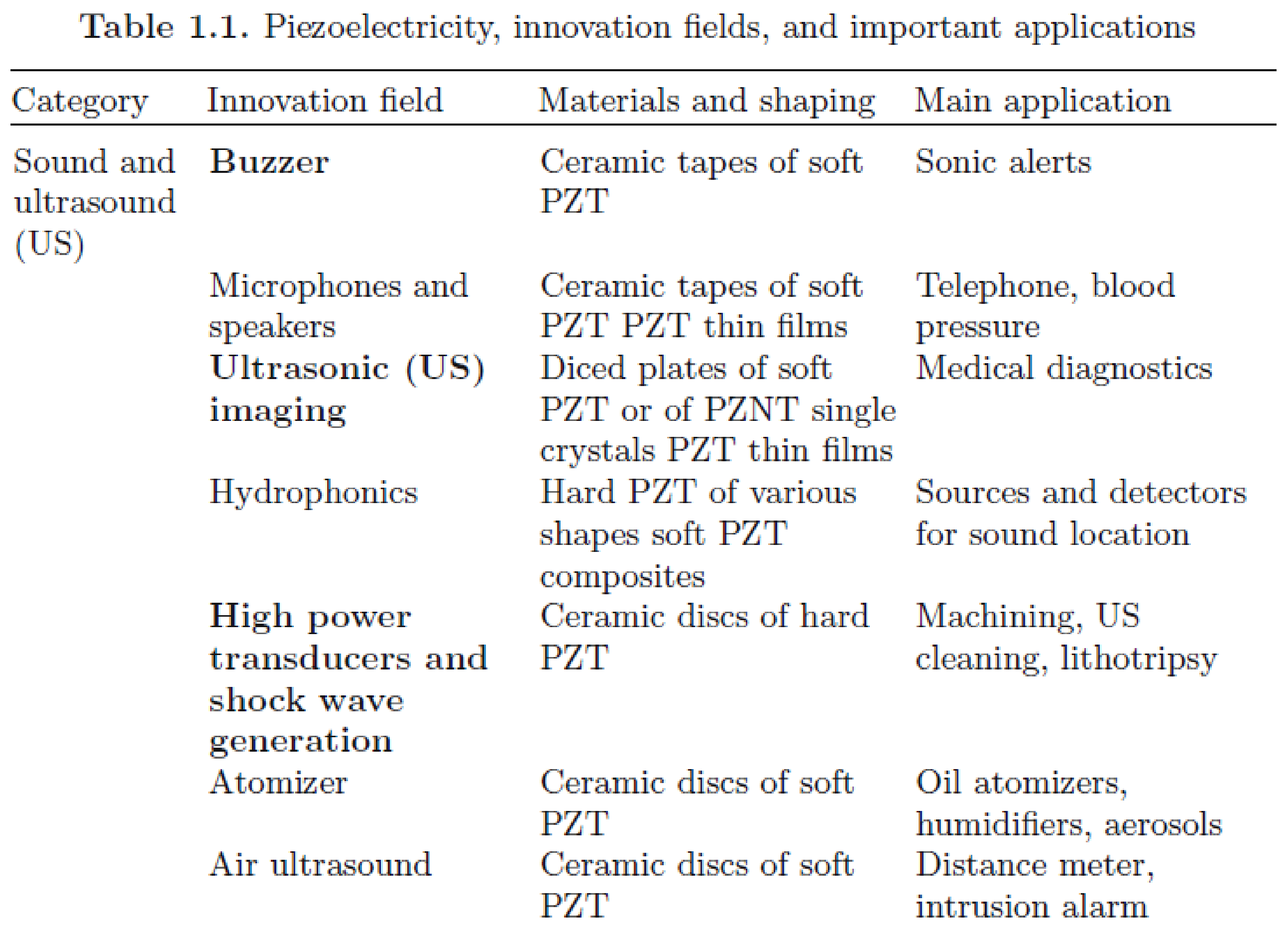


Table 1.1. Piezoelectricity, innovation fields, and important applications

Category	Innovation field	Materials and shaping	Main application
Sound and ultrasound (US)	**Buzzer**	Ceramic tapes of soft PZT	Sonic alerts
	Microphones and speakers	Ceramic tapes of soft PZT PZT thin films	Telephone, blood pressure
	Ultrasonic (US) imaging	Diced plates of soft PZT or of PZNT single crystals PZT thin films	Medical diagnostics
	Hydrophonics	Hard PZT of various shapes soft PZT composites	Sources and detectors for sound location
	High power transducers and shock wave generation	Ceramic discs of hard PZT	Machining, US cleaning, lithotripsy
	Atomizer	Ceramic discs of soft PZT	Oil atomizers, humidifiers, aerosols
	Air ultrasound	Ceramic discs of soft PZT	Distance meter, intrusion alarm

Book: W. Heywang, et al. *Piezoelectricity: evolution and future of a technology*. Vol. 114. Springer Science & Business Media, 2008.

کاربردهای پیزوالکتریک

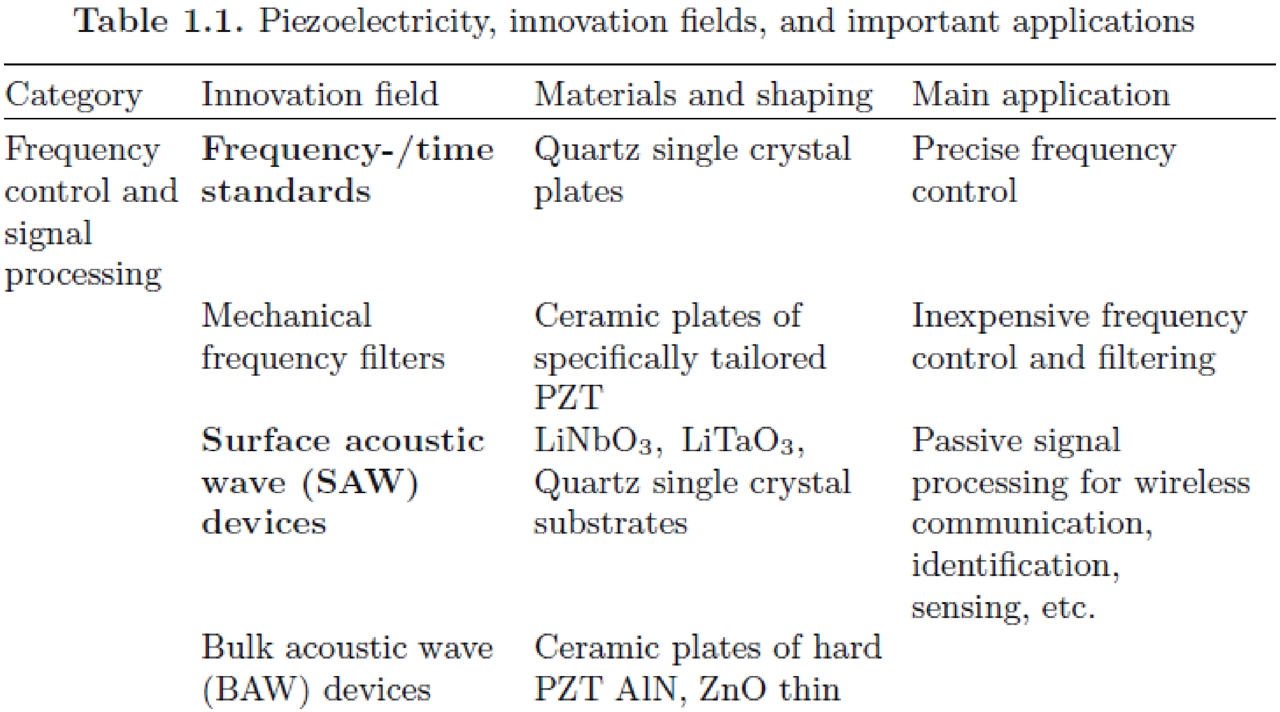


Table 1.1. Piezoelectricity, innovation fields, and important applications

Category	Innovation field	Materials and shaping	Main application
Frequency control and signal processing	**Frequency-/time standards**	Quartz single crystal plates	Precise frequency control
	Mechanical frequency filters	Ceramic plates of specifically tailored PZT	Inexpensive frequency control and filtering
	Surface acoustic wave (SAW) devices	$LiNbO_3$, $LiTaO_3$, Quartz single crystal substrates	Passive signal processing for wireless communication, identification, sensing, etc.
	Bulk acoustic wave (BAW) devices	Ceramic plates of hard PZT AlN, ZnO thin	

Book: W. Heywang, et al. *Piezoelectricity: evolution and future of a technology*. Vol. 114. Springer Science & Business Media, 2008.

کاربردهای خاصیت پیزوالکتریک

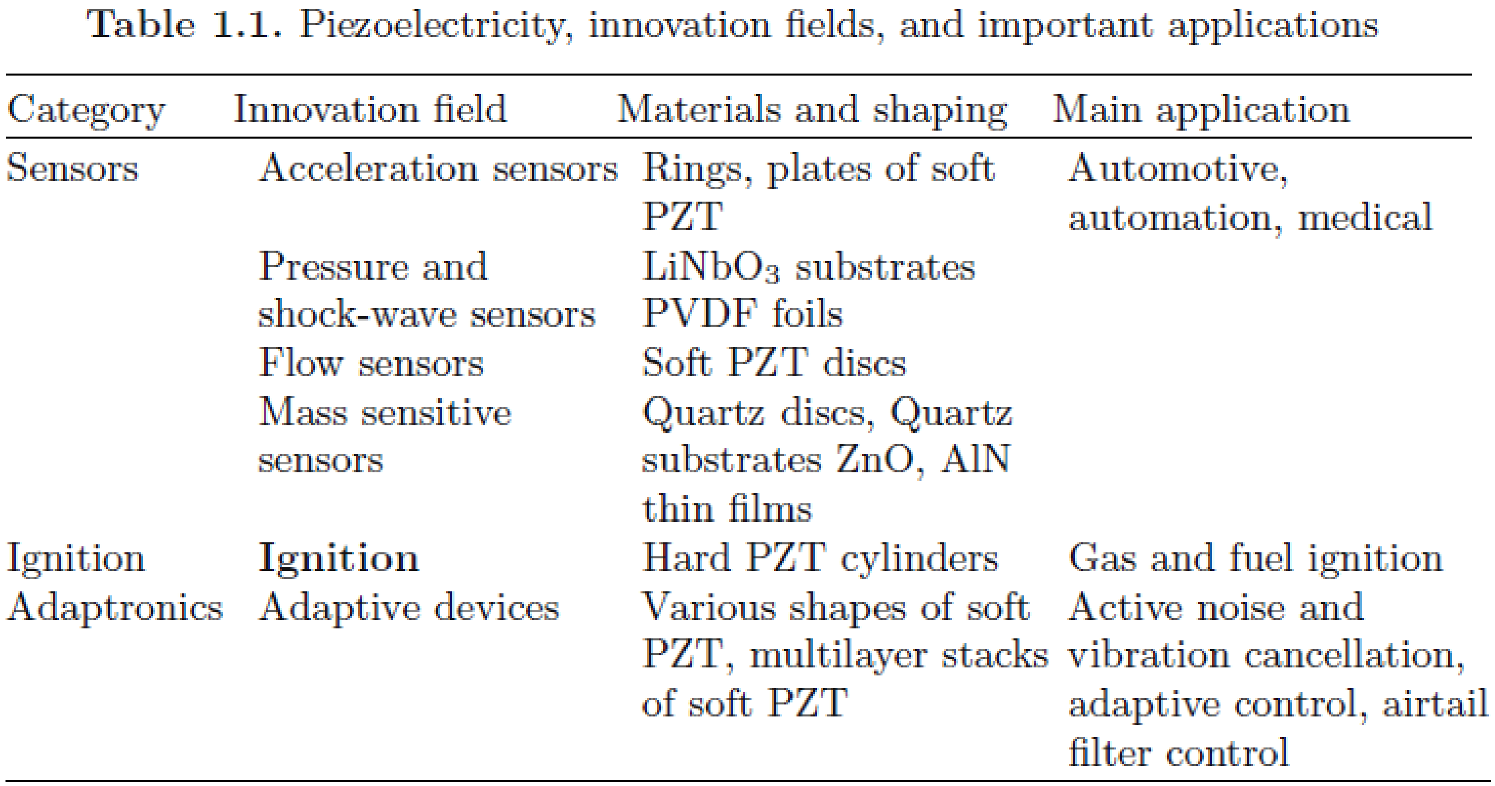


Table 1.1. Piezoelectricity, innovation fields, and important applications

Category	Innovation field	Materials and shaping	Main application
Sensors	Acceleration sensors	Rings, plates of soft PZT	Automotive, automation, medical
	Pressure and shock-wave sensors	$LiNbO_3$ substrates PVDF foils	
	Flow sensors	Soft PZT discs	
	Mass sensitive sensors	Quartz discs, Quartz substrates ZnO, AlN thin films	
Ignition	**Ignition**	Hard PZT cylinders	Gas and fuel ignition
Adaptronics	Adaptive devices	Various shapes of soft PZT, multilayer stacks of soft PZT	Active noise and vibration cancellation, adaptive control, airtail filter control

Book: W. Heywang, et al. *Piezoelectricity: evolution and future of a technology*. Vol. 114. Springer Science & Business Media, 2008.

مقایسه مواد پیزوالکتریک

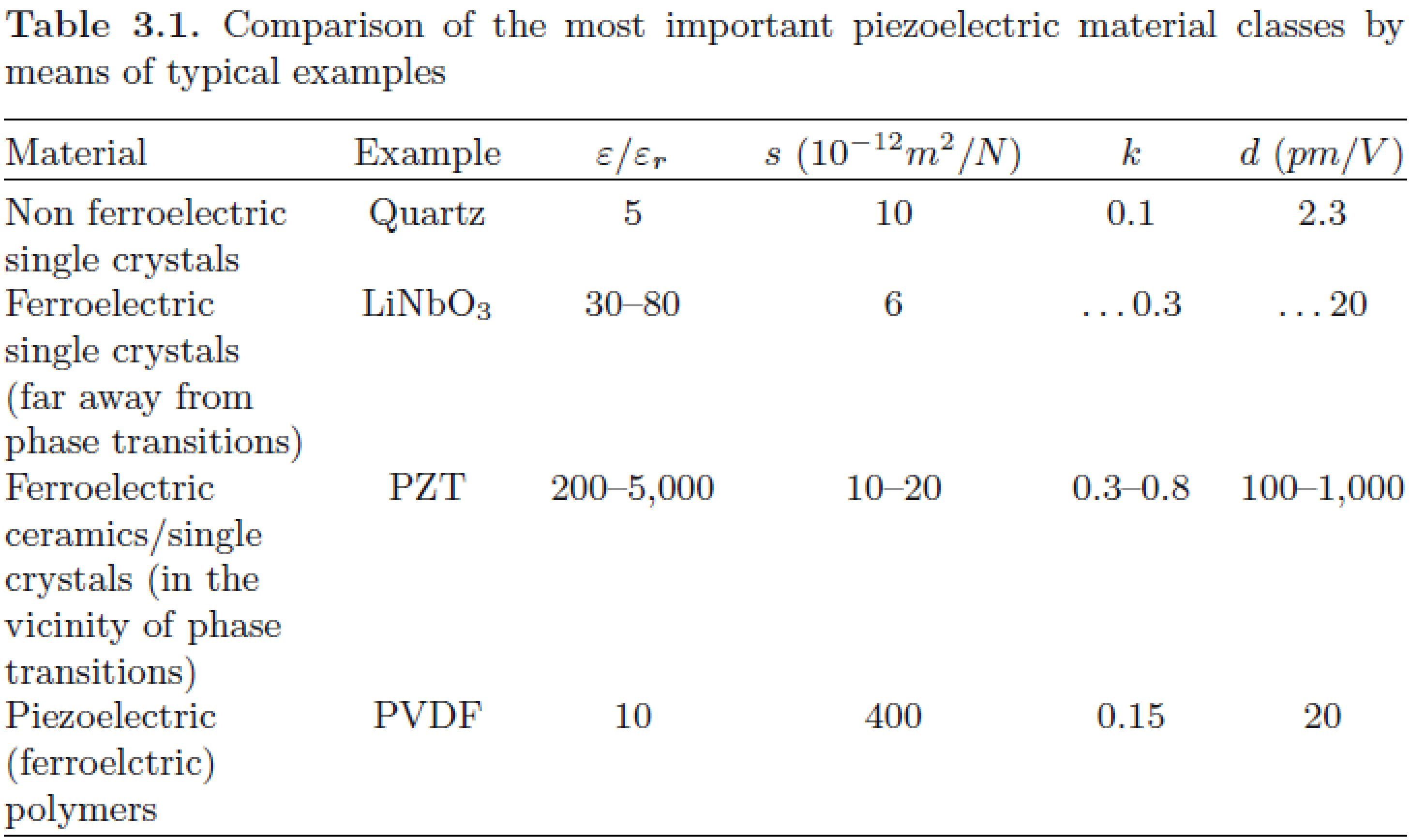


Table 3.1. Comparison of the most important piezoelectric material classes by means of typical examples

Material	Example	$\varepsilon/\varepsilon_r$	$s\ (10^{-12}m^2/N)$	k	$d\ (pm/V)$
Non ferroelectric single crystals	Quartz	5	10	0.1	2.3
Ferroelectric single crystals (far away from phase transitions)	$LiNbO_3$	30–80	6	…0.3	…20
Ferroelectric ceramics/single crystals (in the vicinity of phase transitions)	PZT	200–5,000	10–20	0.3–0.8	100–1,000
Piezoelectric (ferroelctric) polymers	PVDF	10	400	0.15	20

Book: W. Heywang, et al. *Piezoelectricity: evolution and future of a technology*. Vol. 114. Springer Science & Business Media, 2008.

مدل مداری برای مولد پیزوالکتریک

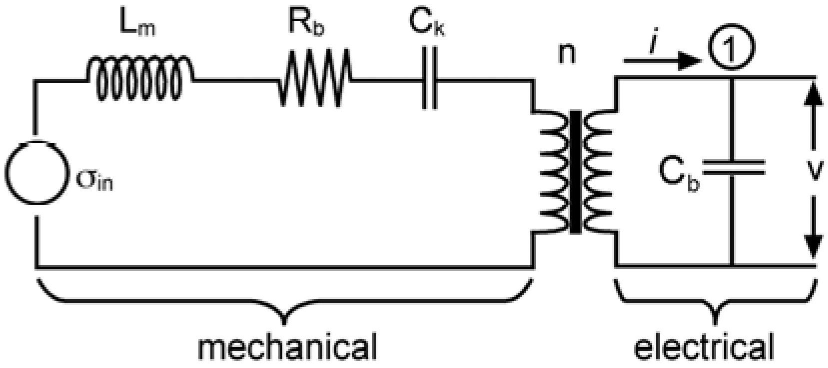
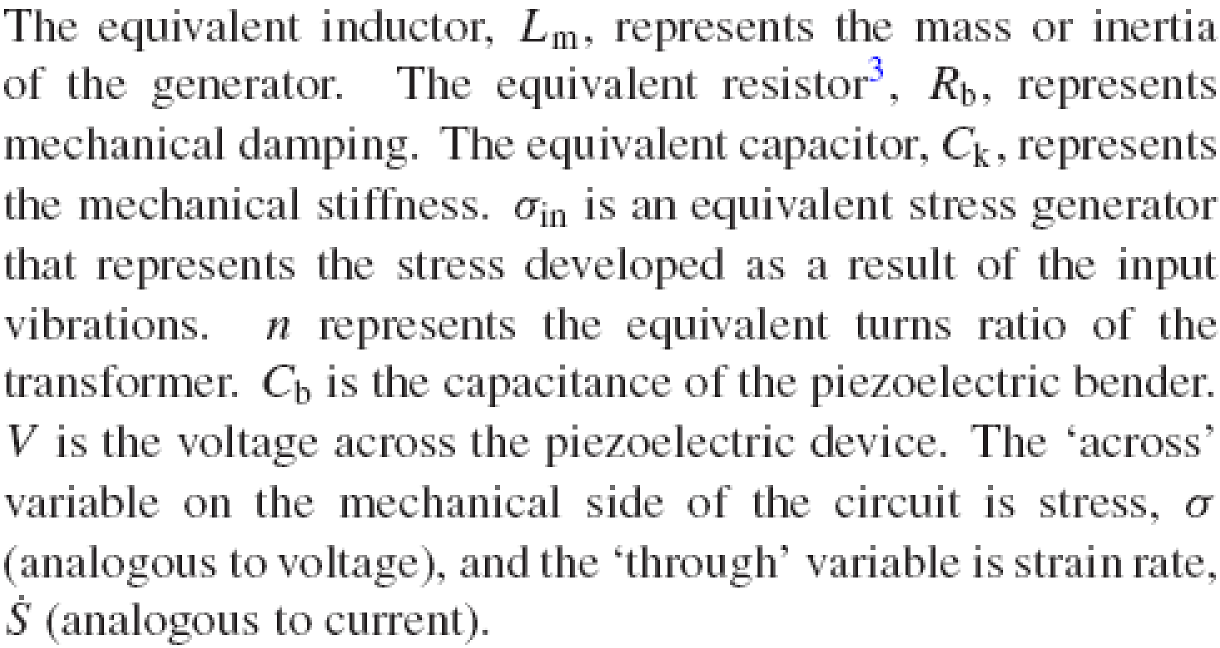


Figure 2. Circuit representation of the piezoelectric generator. (Note that node 1 is used in the derivation of equation (5).)

$$\sigma_{\mathrm{in}} = L_{\mathrm{m}}\ddot{S} + R_{\mathrm{b}}\dot{S} + \frac{S}{C_{\mathrm{k}}} + nV \qquad (5)$$

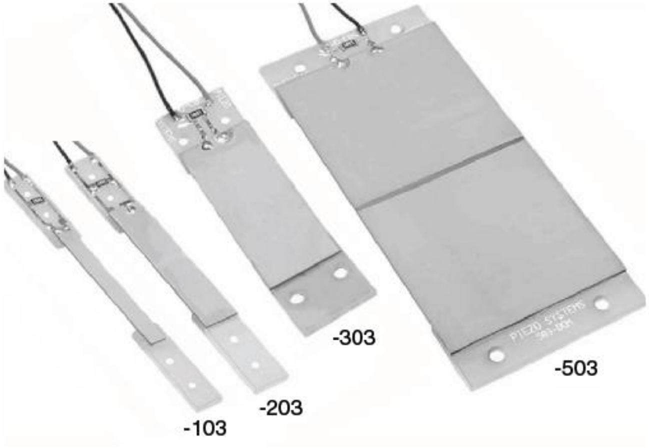
$$i = C_{\mathrm{b}}\dot{V}. \qquad (6)$$

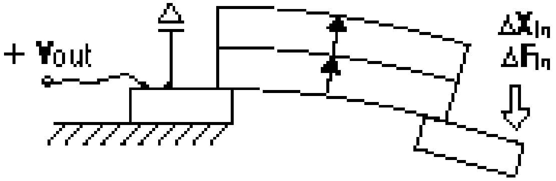


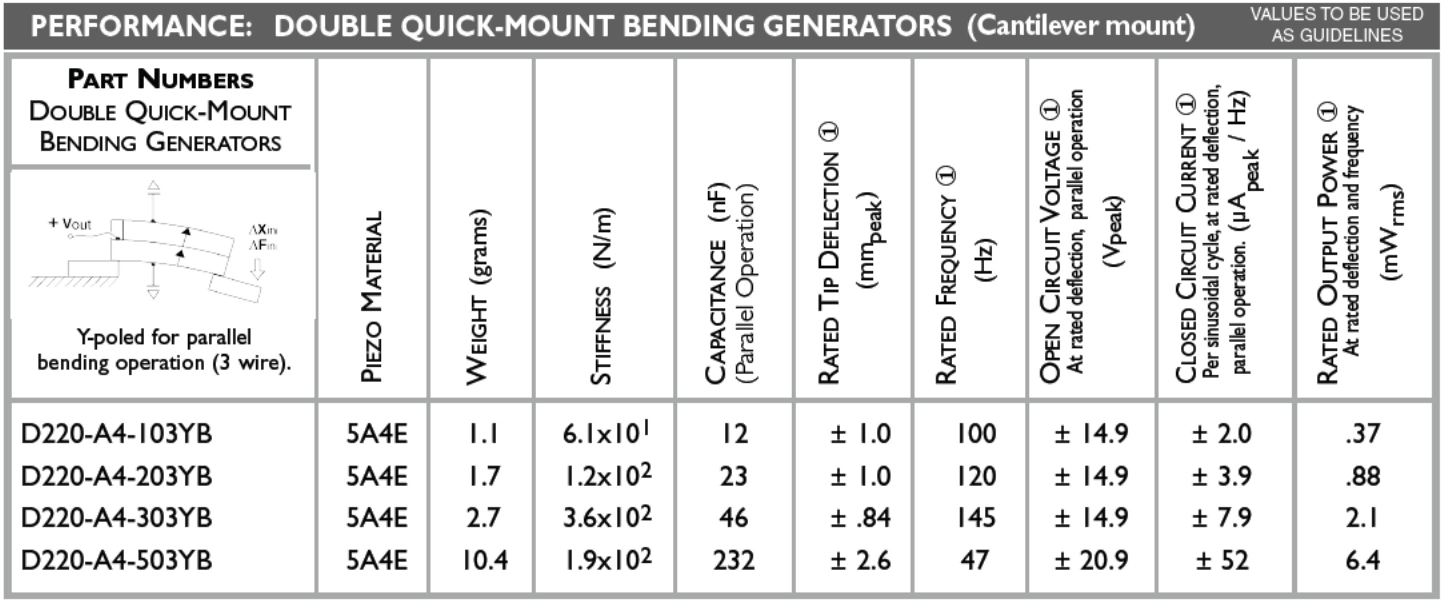
The equivalent inductor, L_{m}, represents the mass or inertia of the generator. The equivalent resistor[3], R_{b}, represents mechanical damping. The equivalent capacitor, C_{k}, represents the mechanical stiffness. σ_{in} is an equivalent stress generator that represents the stress developed as a result of the input vibrations. n represents the equivalent turns ratio of the transformer. C_{b} is the capacitance of the piezoelectric bender. V is the voltage across the piezoelectric device. The 'across' variable on the mechanical side of the circuit is stress, σ (analogous to voltage), and the 'through' variable is strain rate, $\dot{S}$ (analogous to current).

Roundy, Shad, and Paul K. Wright. "A piezoelectric vibration based generator for wireless electronics." *Smart Materials and structures* 13.5 (2004): 1131.

حسگر پیزو الکتریک







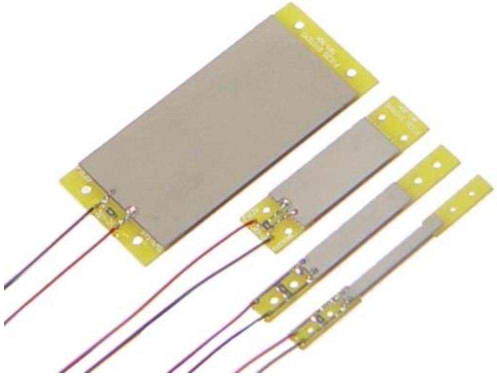
PERFORMANCE: DOUBLE QUICK-MOUNT BENDING GENERATORS (Cantilever mount)

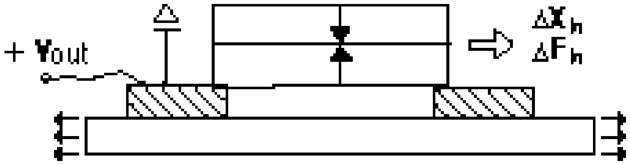
VALUES TO BE USED AS GUIDELINES

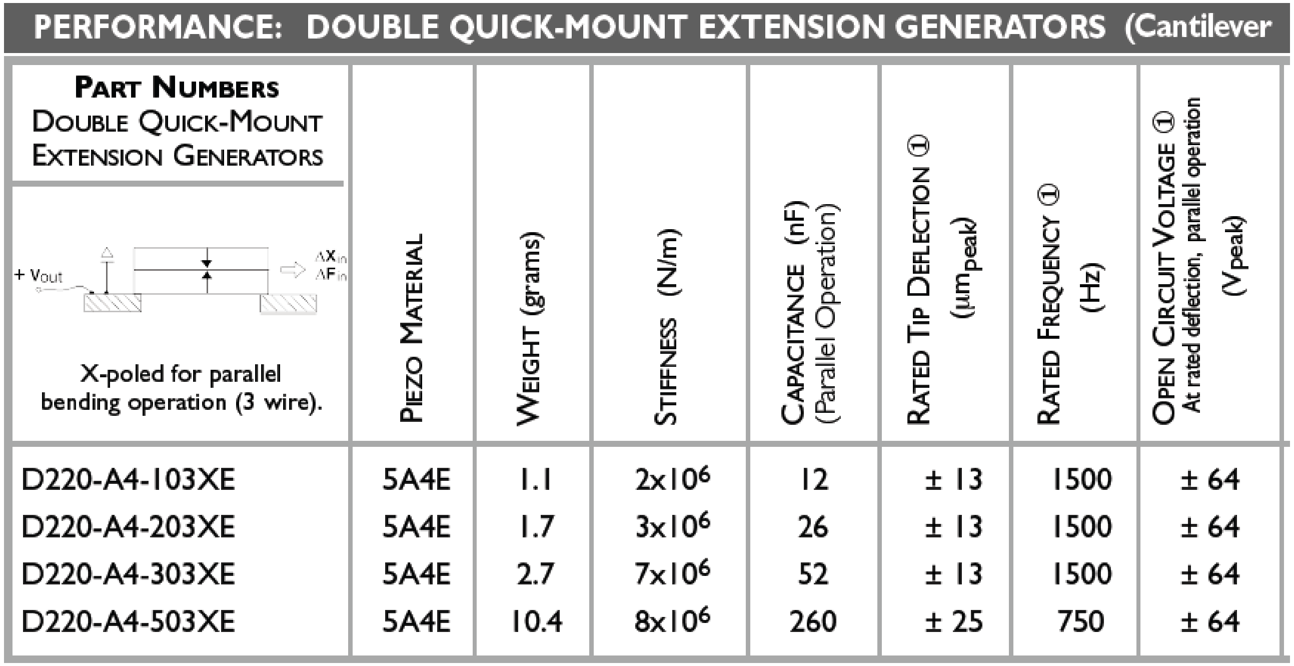
PART NUMBERS DOUBLE QUICK-MOUNT BENDING GENERATORS Y-poled for parallel bending operation (3 wire).	PIEZO MATERIAL	WEIGHT (grams)	STIFFNESS (N/m)	CAPACITANCE (nF) (Parallel Operation)	RATED TIP DEFLECTION ① (mm_{peak})	RATED FREQUENCY ① (Hz)	OPEN CIRCUIT VOLTAGE ① At rated deflection, parallel operation (Vpeak)	CLOSED CIRCUIT CURRENT ① Per sinusoidal cycle, at rated deflection, parallel operation. (μA_{peak} / Hz)	RATED OUTPUT POWER ① At rated deflection and frequency (mW_{rms})
D220-A4-103YB	5A4E	1.1	6.1×10^{1}	12	± 1.0	100	± 14.9	± 2.0	.37
D220-A4-203YB	5A4E	1.7	1.2×10^{2}	23	± 1.0	120	± 14.9	± 3.9	.88
D220-A4-303YB	5A4E	2.7	3.6×10^{2}	46	± .84	145	± 14.9	± 7.9	2.1
D220-A4-503YB	5A4E	10.4	1.9×10^{2}	232	± 2.6	47	± 20.9	± 52	6.4

Piezo Systems Company- http://www.piezo.com

حسگر پیزو الکتریک







PERFORMANCE: DOUBLE QUICK-MOUNT EXTENSION GENERATORS (Cantilever

PART NUMBERS DOUBLE QUICK-MOUNT EXTENSION GENERATORS X-poled for parallel bending operation (3 wire).	PIEZO MATERIAL	WEIGHT (grams)	STIFFNESS (N/m)	CAPACITANCE (nF) (Parallel Operation)	RATED TIP DEFLECTION ① (μm_{peak})	RATED FREQUENCY ① (Hz)	OPEN CIRCUIT VOLTAGE ① At rated deflection, parallel operation (V_{peak})
D220-A4-103XE	5A4E	1.1	2×10^6	12	± 13	1500	± 64
D220-A4-203XE	5A4E	1.7	3×10^6	26	± 13	1500	± 64
D220-A4-303XE	5A4E	2.7	7×10^6	52	± 13	1500	± 64
D220-A4-503XE	5A4E	10.4	8×10^6	260	± 25	750	± 64

Piezo Systems Company- http://www.piezo.com

Product Names

ماده مورد استفاده در حسگر پیزو الکتریک

PSI-5A4E & PSI-5H4E

Chemical Family: Ceramic Materials

Hazardous Component	CAS#	%
Lead Oxide	1317-36-8	60-72
Zirconium Oxide	1314-23-4	5-25
Titanium Oxide	13463-67-7	5-15
Lanthanum Oxide	1312-81-8	0-4
Niobium Oxide	1313-96-8	0-20
Nickel Oxide	1313-99-1	0-7

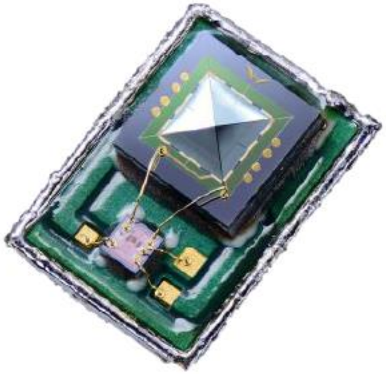
میکروفن پیزو الکتریک

SPM04C

Low-Noise Bottom Port Piezoelectric MEMS Microphone

FEATURES

- Unique piezoelectric MEMS transducer
- Very-low noise floor
- Low part-to-part variation
- High dynamic range
- Flat frequency response
- Durable piezoelectric MEMS construction
- Small size
- Waterproof



APPLICATIONS

- Smartphones
- Wearables
- Smart home devices
- Video cameras
- IoT devices **Internet of Things** (IoT)
- Automotive

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