Le Proprietà Elettriche

Tra i minerali non conduttori si individuano:

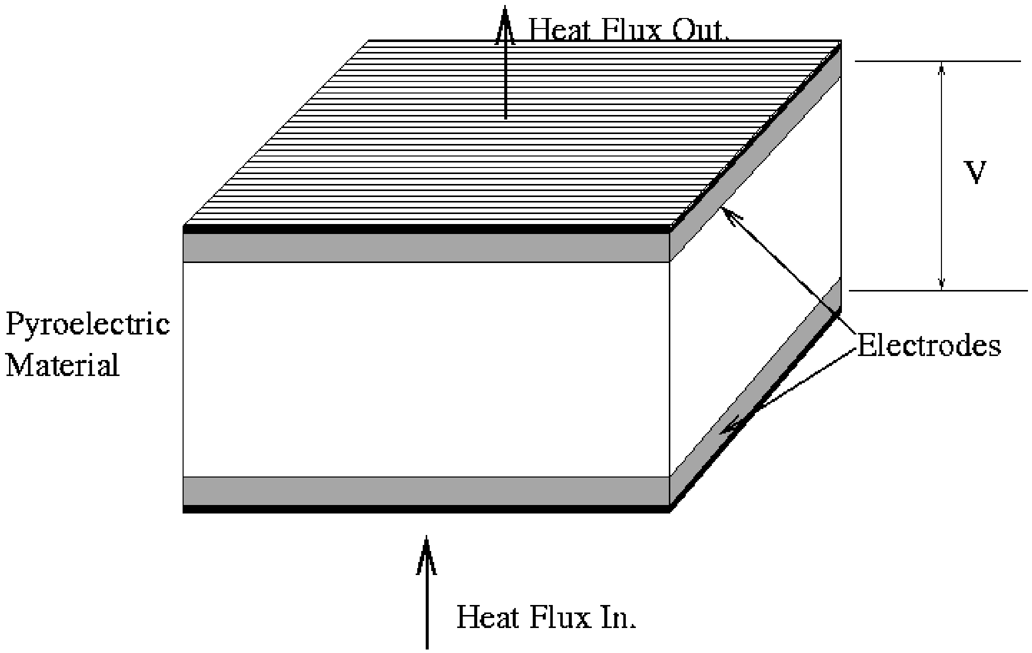
- **Minerali Piroelettrici: sviluppano una differenza di potenziale se sottoposti a riscaldamento;**
- **Minerali Piezoelettrici: sviluppano una differenza di potenziale se sottoposti a sollecitazioni di tipo meccanico (compressione, trazione o torsione). Al contrario, quando si applica una differenza di potenziale al cristallo, esso si espande o si contrae.**

Quarzo

L'effetto piezoelettrico ha importanza tecnologica (ultrasuoni, stabilizzatori di frequenza, trasduttori di pressione, oscillatori per misurare il tempo…)

Pyroelectric Effect.

Generation of electric charge by a crystalline material when subjected to a heat flow.



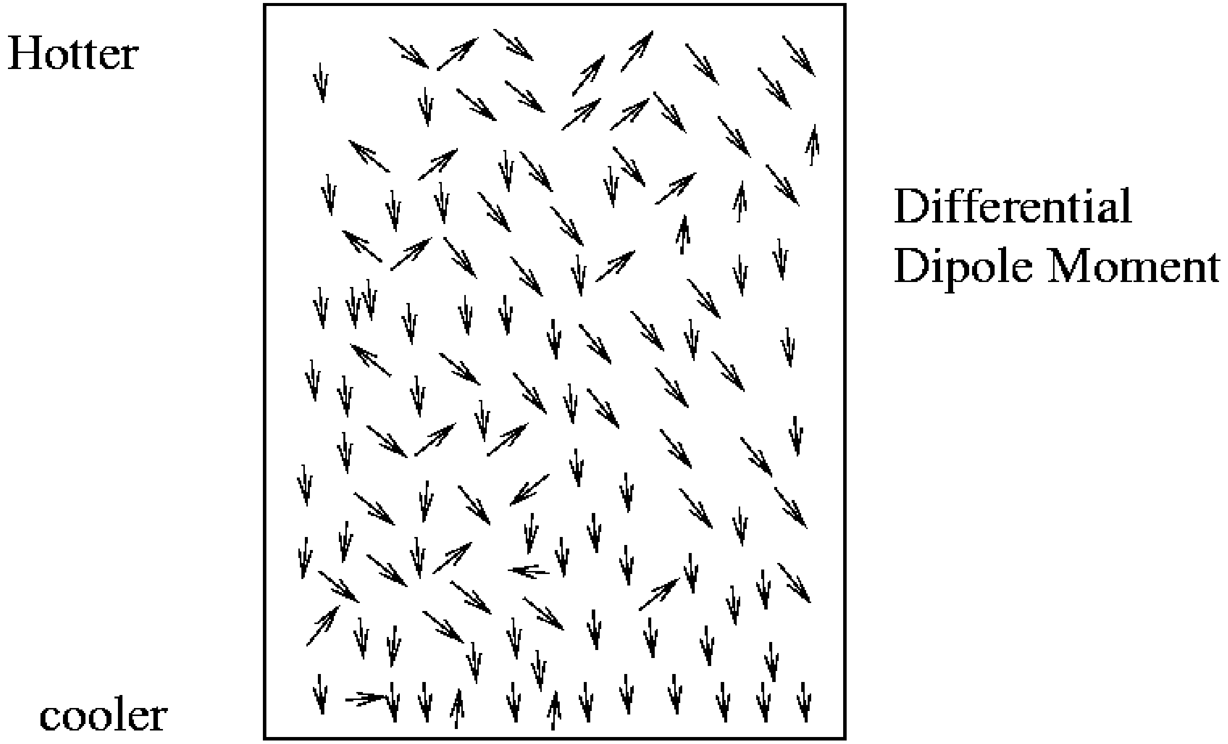
Closely related to Piezoelectricity.

$BaTiO_3$, PZT and PVDF all exhibit Pyroelectric effects

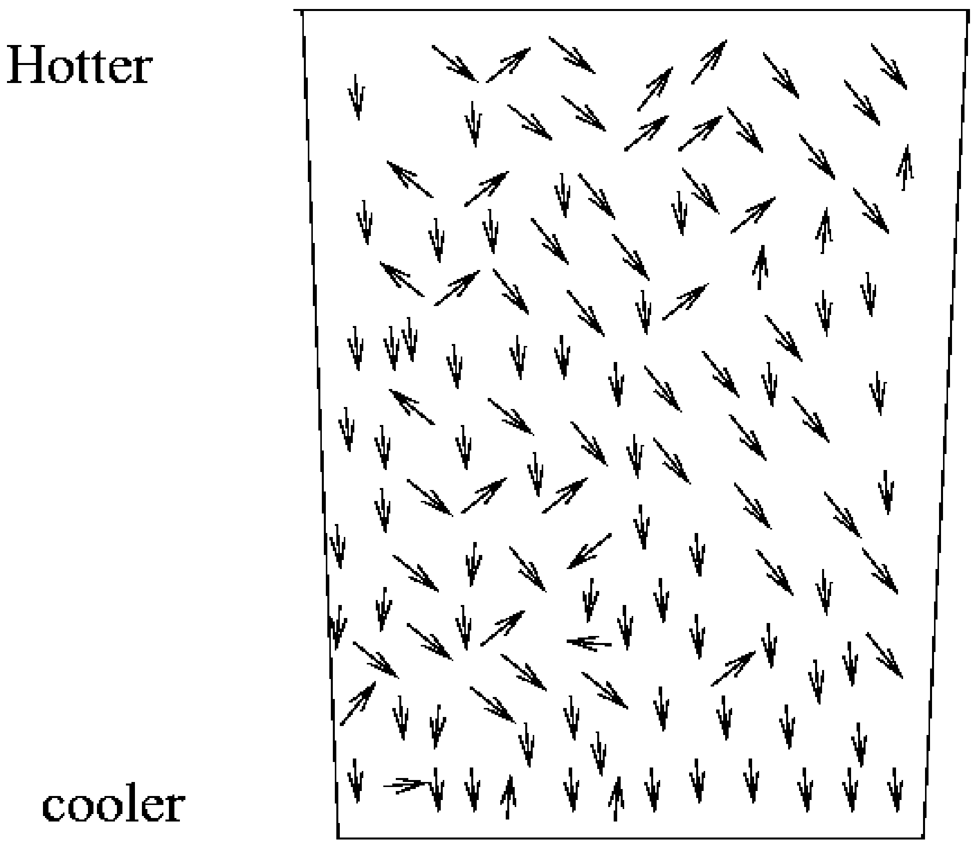
Primary Pyroelectricity.

Temperature changes shortens or elongates individual dipoles.

This affects randomness of dipole orientations due to thermal agitation.



Secondary Pyroelectricity



Differential temperature
Induces a strain
Causing Piezoelectricity

Quantitative Pyroelectricity.

Pyroelectric crystals are transducers: they convert thermal to electrical energy.

The Dipole moment of the bulk pyroelectric is:

$$M = \mu A h$$

Where μ is the dipole moment per unit volume, A is the sensor area and h is the thickness

From standard dielectrics, charge on electrodes, $Q = \mu A$

The dipole moment, μ, varies with temperature.

$$P_Q = \frac{dP_S}{dT}$$

Is the pyroelectric charge coefficient, and P_s is the "spontaneous polarisation"

The generated charge is $\Delta Q = P_Q A \Delta T$

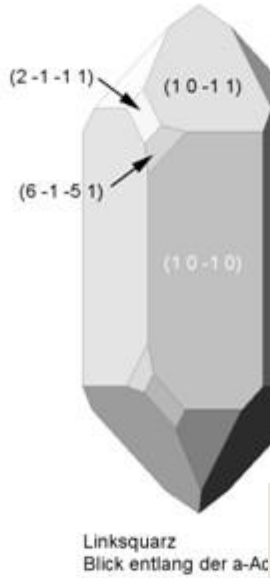
$P_v = \dfrac{dE}{dT}$ is the pyroelectric voltage coefficient and E is the electric field.

The generated voltage is $\Delta V = P_v h \Delta T$ (h is the thickness)

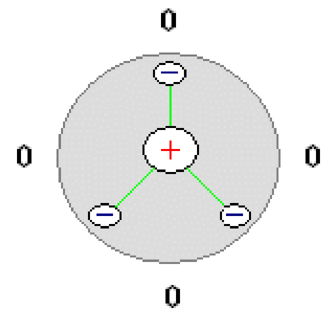
The relation between charge and voltage coefficients follows directly from Q = CV

$$\frac{P_Q}{P_V} = \frac{dP_S}{dE} = \varepsilon_r \varepsilon_0$$

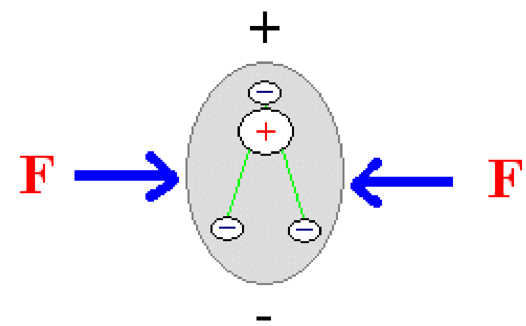
Minerali Piezoelettrici: il caso del quarzo

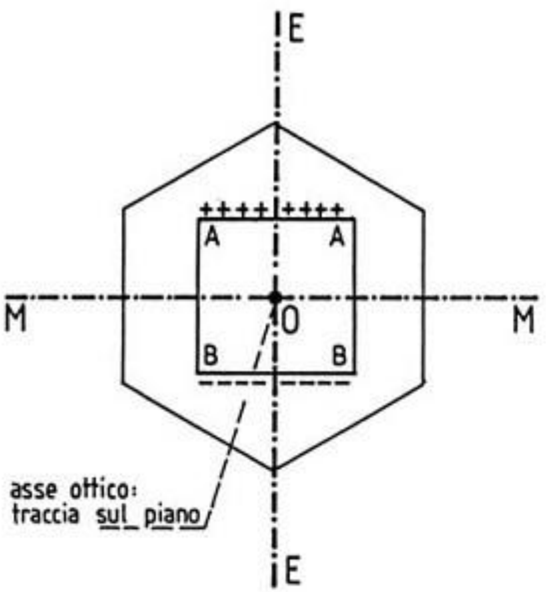


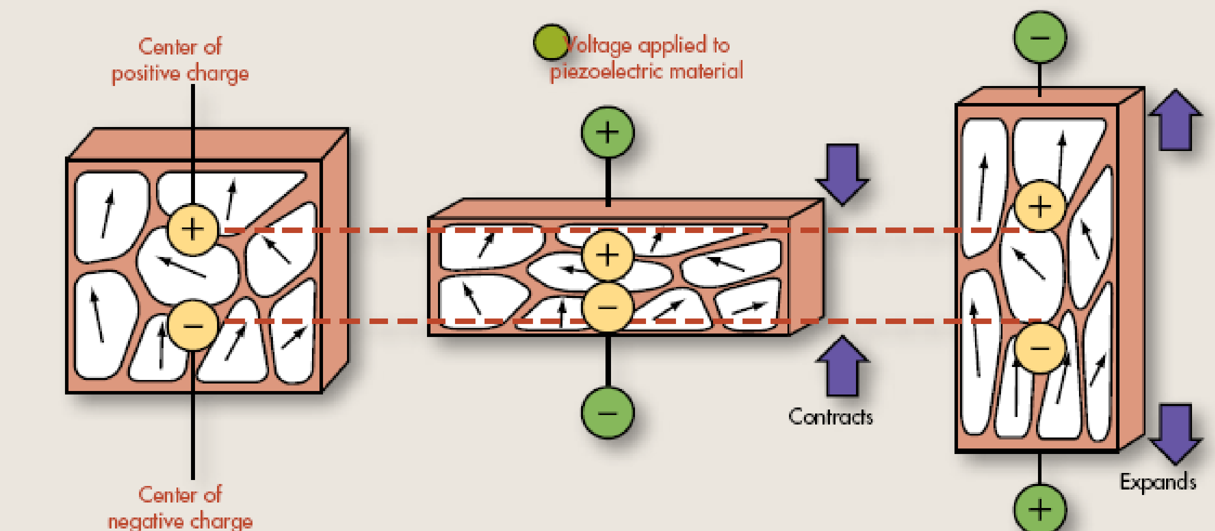
Inizialmente il materiale è neutro, ossia sulla superficie non vi è un accumulo di carica.



Sottoposto alla forza F il cristallo si "deforma" creando un'accumulo di carica positiva su un lato della sua superficie ed un accumulo di carica di segno opposto nella superficie opposta. Si crea cioè un DIPOLO.



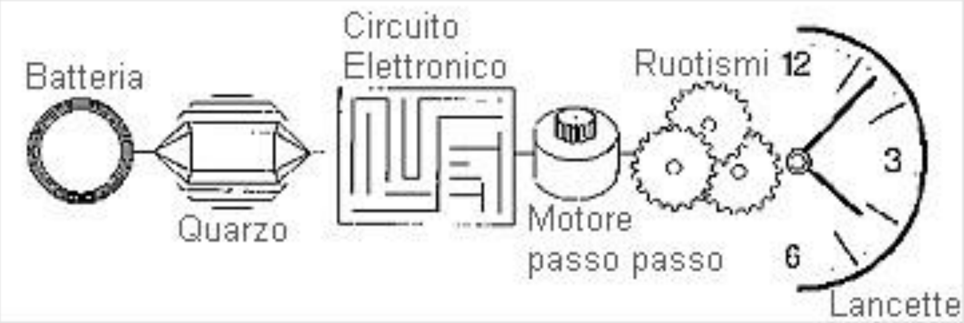




1. The piezoelectric effect causes crystal materials like quartz to generate an electric charge when the crystal material is compressed, twisted, or pulled. The reverse also is true, as the crystal material compresses or expands when an electric voltage is applied.

Minerali Piezoelettrici: il caso del quarzo
Utilizzo di cristalli di quarzo negli orologi

Nel 1880 i fratelli Curie scoprirono che il tempo poteva essere suddiviso in intervalli supposti eguali tra loro sfruttando il fenomeno della "piezoelettricità"" in quanto osservarono che il cristallo di quarzo (biossido di silicio) percorso da una corrente continua (DC) si contrae e si allunga, mentre il quarzo percorso da una corrente alternata (AC) comincia a vibrare fino ad entrare in risonanza costante.
A questo punto il quarzo percorso dalla corrente comincia a vibrare e se la frequenza di eccitazione è uguale alla frequenza propria del cristallo (dipende dalle sue dimensioni, dai valori delle sue costanti elastiche e variabile in funzione del tipo di eccitazione fornitagli), entrerà in risonanza emettendo, un segnale costante con una frequenza di 32.768 Hz (Hertz) (1 Hz = 1 oscillazione al secondo)
Questo segnale costante viene trasmesso al circuito integrato (demoltiplicatore di frequenza), che è costituito da una serie di multivibratori bistabili (flip-flop) tali da ricevere in entrata una frequenza di 32.768 Hz e restituirla in uscita generalmente con una frequenza di 1 Hz., permette di inviare alla bobina un'energia pulsante costante che va ad alimentare il motore "passo passo" dell'orologio che trasforma l'energia elettrica in meccanica.



Piezoelectric effect

- Discovered in 1880 by Jacques and Pierre Curie during studies into the effect of pressure on the generation of electrical charge by crystals (such as quartz).
- Piezoelectricity is defined as a change in electric polarization with a change in applied stress (direct piezoelectric effect).
- The converse piezoelectric effect is the change of strain or stress in a material due to an applied electric field.

Piezoelectric effect

- The linear relationship between stress X_{ik} applied to a piezoelectric material and resulting charge density D_i is known as the direct piezoelectric effect and may be written as

$$D_i = d_{ijk} X_{jk}$$

- where d_{ijk} (C N^{-1}) is a third-rank tensor of piezoelectric coefficients.

Piezoelectric effect

- Another interesting property of piezoelectric material is they change their dimensions (contract or expand) when an electric field is applied to them.
- The converse piezoelectric effect describes the strain that is developed in a piezoelectric material due to the applied electric field:

$$x_{ij} = d_{kij} E_k = d^t_{ijk} E_k$$

- where *t* denotes the transposed matrix.
- The units of the converse piezoelectric coefficient are (m V^{-1}).

Piezoelectric effect

- The piezoelectric coefficients, *d* for the direct and converse piezoelectric effects are thermodynamically identical, i.e.

  $$d_{\text{direct}} = d_{\text{converse}}.$$

- Note that the sign of the piezoelectric charge D_i and strain x_{ij} depends on the direction of the mechanical and electric fields, respectively.
- The piezoelectric coefficient *d* can be either positive or negative.

Piezoelectric effect

- It is common to call a piezoelectric coefficient measured in the direction of applied field the longitudinal coefficient, and that measured in the direction perpendicular to the field the transverse coefficient.
- Other piezoelectric coefficients are known as shear coefficients.
- Because the strain and stress are symmetrical tensors, the piezoelectric coefficient tensor is symmetrical with respect to the same indices,

$$d_{ijk} = d_{ikj} \, .$$

Piezoelectricity

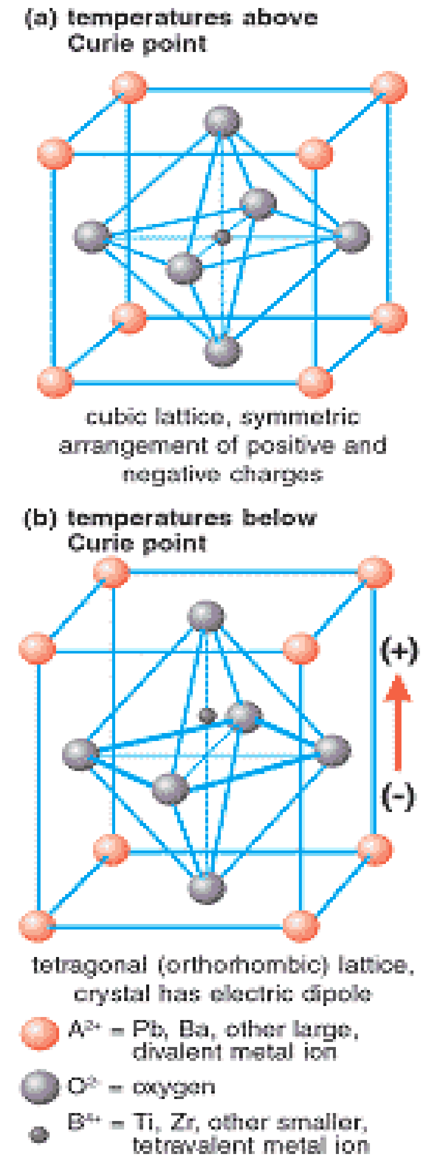
- The microscopic origin of the piezoelectric effect is the displacement of **ionic charges** within a crystal structure.
- In the absence of external strain, the charge distribution is symmetric and the net electric dipole moment is zero.
- However when an external stress is applied, the charges are displaced and the charge distribution is no longer symetric and a net polarization is created.

Piezoelectricity

- In some cases a crystal posses a unique polar axis even in the unstrained condition.
- This can result in a change of the electric charge due to a uniform change of temperature.
- This is called the ***pyroelectric effect***.
- The direct piezoelectric effect is the basis for force, pressure, vibration and acceleration sensors and
- The converse effect for actuator and displacement devices.

How are piezoelectric ceramics made?

- A traditional piezoelectric ceramic is perovskite crystal, each consisting of a small, tetravalent metal ion, usually titanium or zirconium, in a lattice of larger, divalent metal ions, usually lead or barium, and O_2- ions.
- Under conditions that confer tetragonal or rhombohedral symmetry on the crystals, each crystal has a dipole moment.

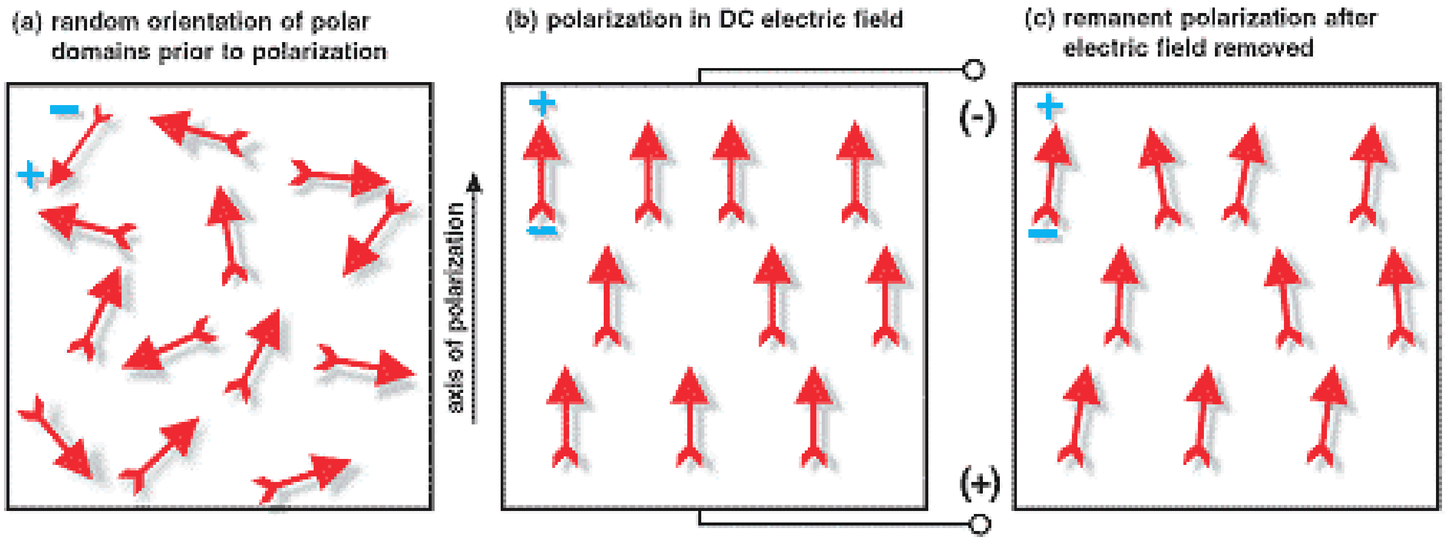


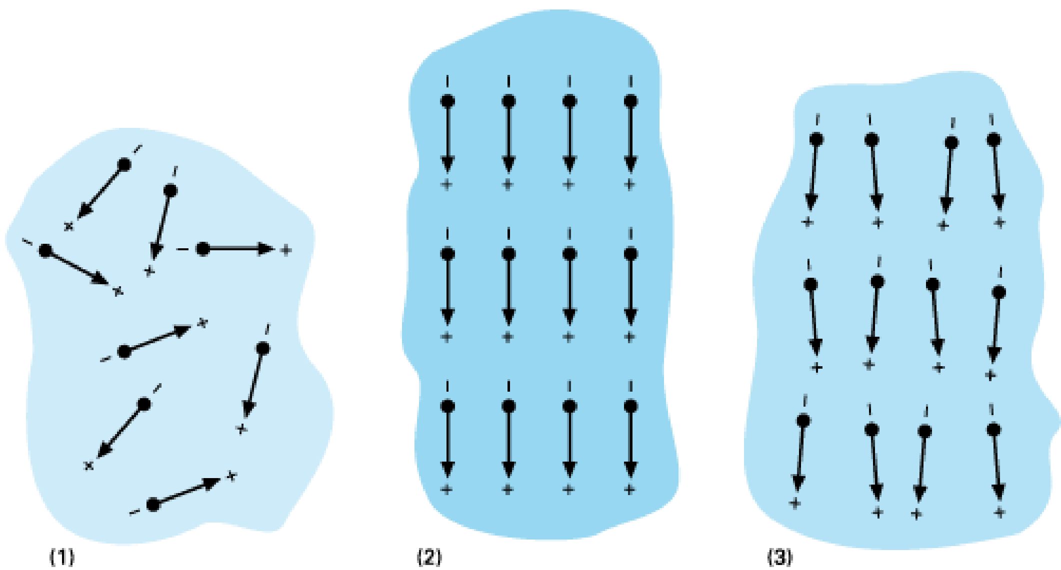
Polarization of piezoelectric

- Above a critical temperature, **the *Curie point***, each perovskite crystal exhibits a simple cubic symmetry with no dipole moment.
- At temperatures below the Curie point, however, each crystal has tetragonal or rhombohedral symmetry and a dipole moment.
- Adjoining dipoles form regions of local alignment called *domains*.
- The alignment gives a net dipole moment to the domain, and thus a net polarization.
- The direction of polarization among neighboring domains is random, however, so the ceramic element has no overall polarization.

Polarization of piezoelectric

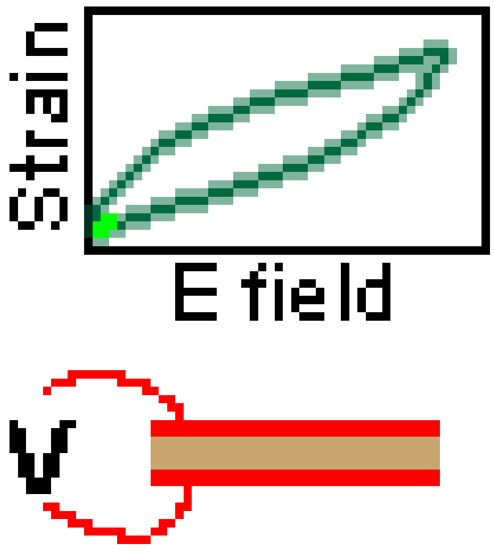
- The domains in a ceramic element are aligned by exposing the element to a strong, direct current electric field, usually at a temperature slightly below the Curie point.
- Through this polarizing *(poling)* treatment, domains most nearly aligned with the electric field expand at the expense of domains that are not aligned with the field, and the element lengthens in the direction of the field.
- When the electric field is removed most of the dipoles are locked into a configuration of near alignment.
- The element now has a permanent polarization, the remanent polarization, and is permanently elongated.



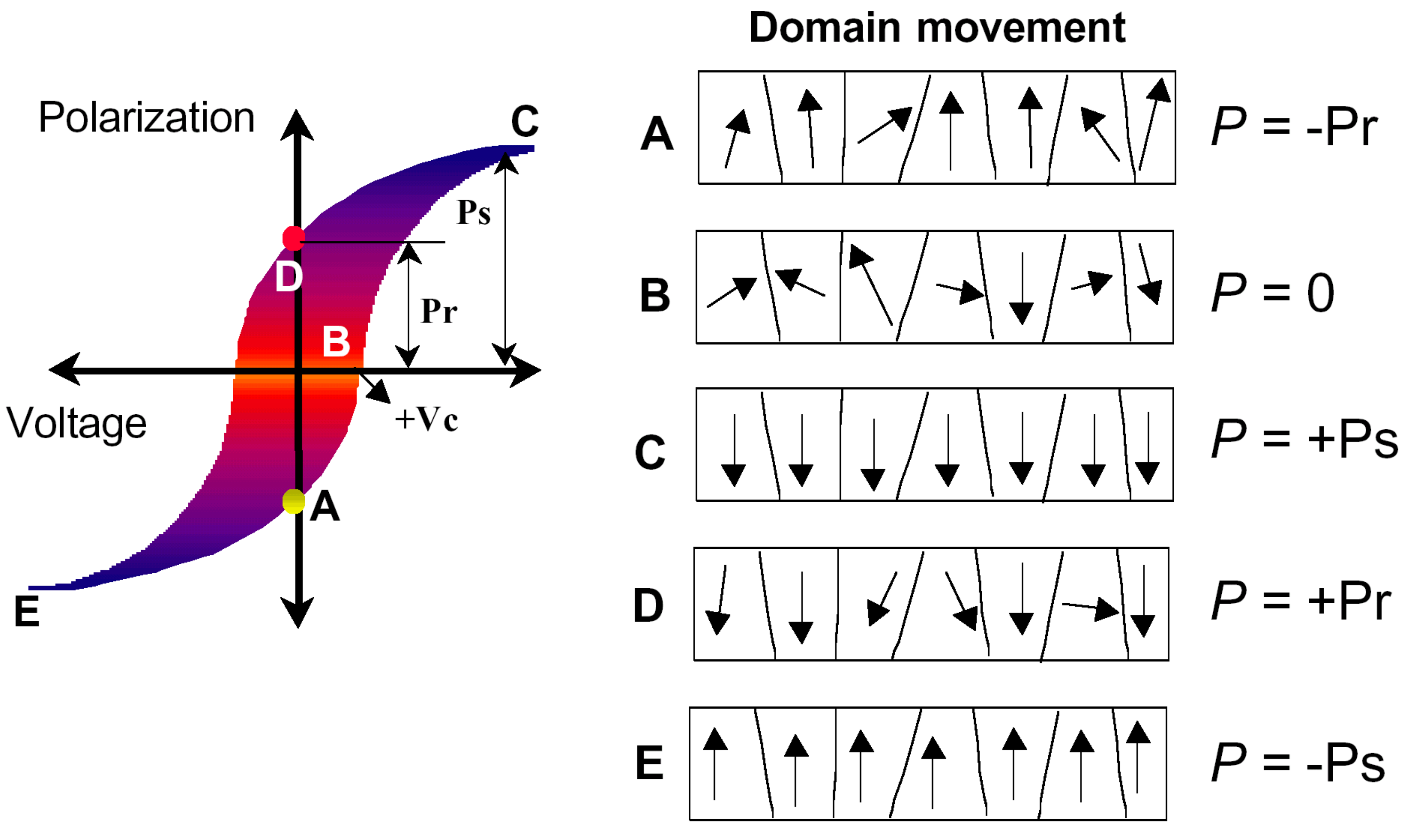


Electric dipoles in Weiss domains; (1) unpoled ferroelectric ceramic, (2) during and (3) after poling (piezoelectric ceramic)

Piezoelectricity



Domain Wall Movement

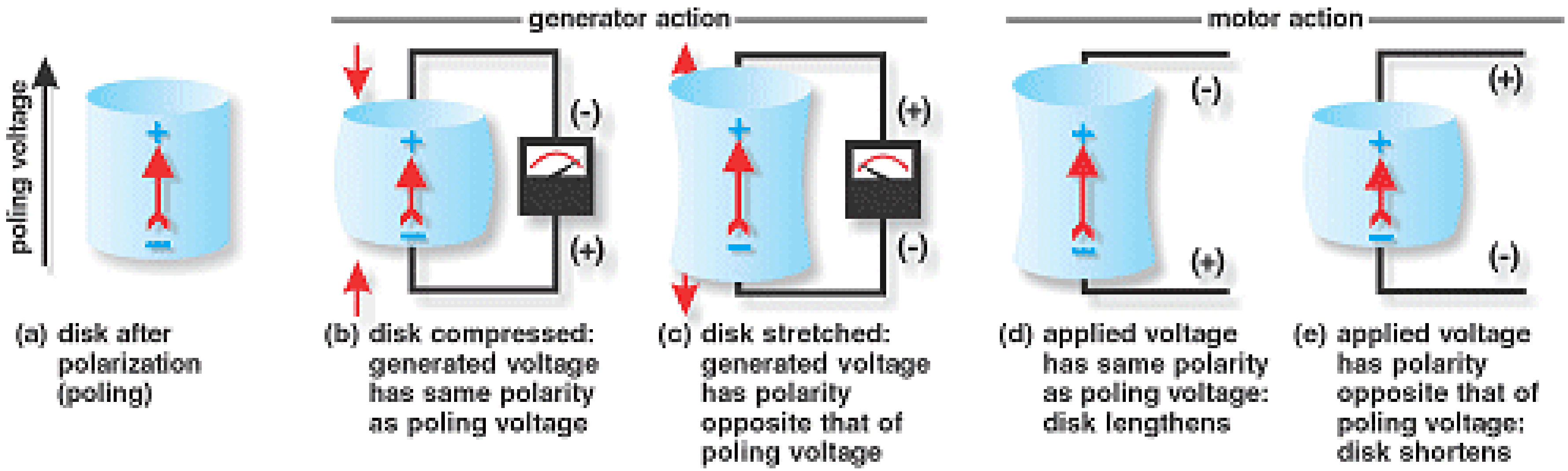


Piezo Materials

- Some examples of practical piezo materials are barium titanate, lithium niobate, polyvinyledene difluoride (PVDF), and lead zirconate titanate (PZT).
- There are several different formulations of the PZT compound, each with different electromechanical properties.

What can piezoelectric ceramics do?

- Mechanical compression or tension on a poled piezoelectric ceramic element changes the dipole moment, creating a voltage.
- Compression along the direction of polarization, or tension perpendicular to the direction of polarization, generates voltage of the same polarity as the poling voltage.



Generator and motor actions of a piezoelectric element

Materiali piezoelettrici

La piezoelettricità si manifesta nei cristalli non dotati di centro di simmetria (21 classi cristallografiche) nei quali il momento di dipolo totale è diverso da zero.

Materiali piezoelettrici naturali: Quarzo, Tormalina, Sale Rochelle $LiNbO_3$, $LiTaO_3$,Langasite, $Li_2B_4O_6$, ZnO;

Materiali piezoelettrici dopo polarizzazione:

Piezoceramici (policristallini): $BaTiO_3$, $PbTiO_3$, PZT, $PbNb_2O_6$;

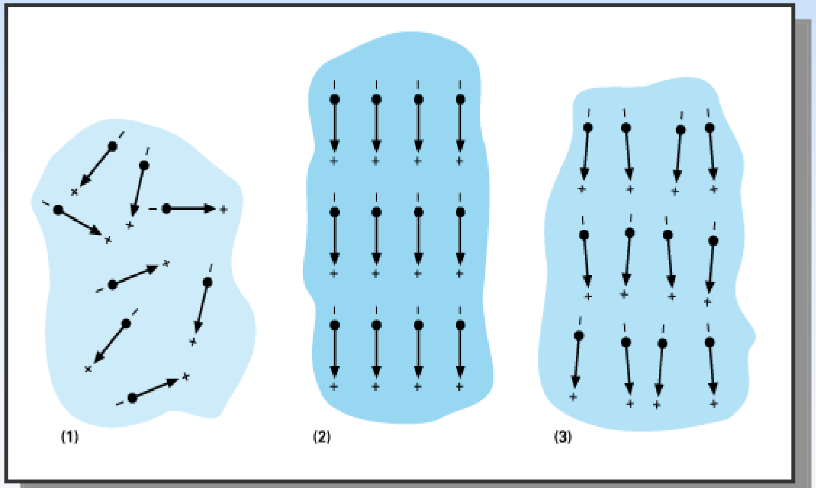
Piezocompositi (polimero-piezoceramico) ;

Piezopolimeri: PVDF, copolimeri di TrFE e TeFE.

Piezoceramici

Materiali policristallini costituiti da un gran numero di grani cristallini orientati casualmente.

Presentano effetto piezoelettrico solo dopo *polarizzazione*: applicazione di un elevato campo elettrico (1-4 MV/m) che orienta i dipoli elettrici interni in un'unica direzione.



***Vantaggi*:**

- **elevata efficienza di trasformazione elettro-meccanica;**
- **buona lavorabilità;**
- **vasto range di forme ottenibili;**
- **produzione in serie.**

Limiti operativi

Depolarizzazione:

- **forti campi elettrici in direzione opposta al campo polarizzante**
- **forti campi elettrici alternati**
- **forti stress meccanici**
- **temperature superiori al punto di Curie.**

Temperatura di Curie:

temperatura alla quale si verifica una transizione di fase nella struttura cristallina tale da determinare la perdita delle proprietà piezoelettriche.

Invecchiamento:

decadimento delle proprietà piezoelettriche man mano che ci si allontana dal momento in cui è avvenuta la polarizzazione.

Piroelettricità: variazione dello stato polarizzato interno con la temperatura.

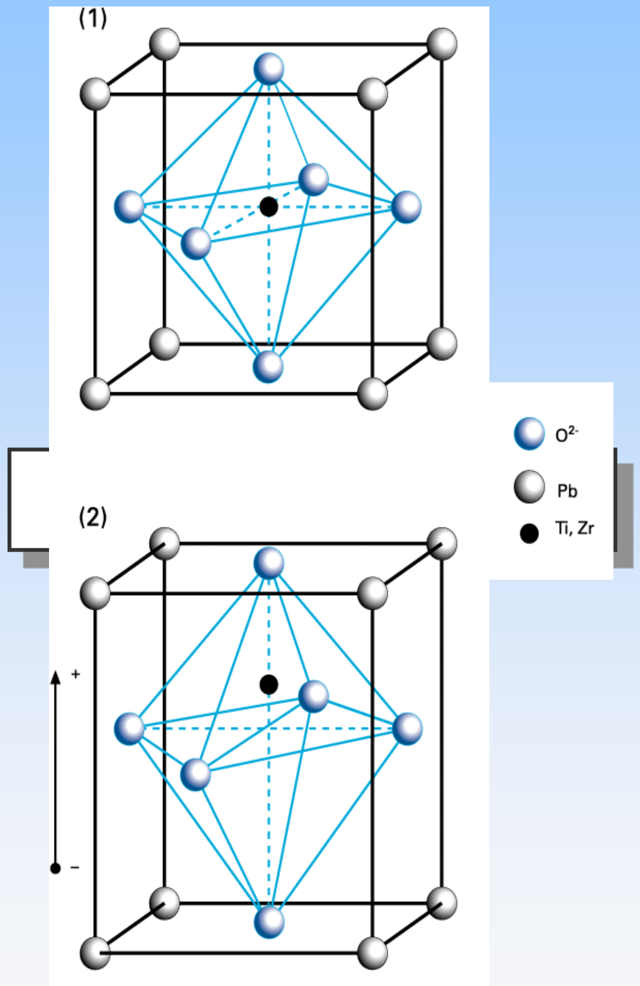
Struttura cristallina

Struttura cristallina <u>perovskite</u>

• per T>Tc la cella elementare ha una struttura cubica simmetrica (cristallo non piezoelettrico)

• per T<Tc la cella elementare ha una struttura tetragonale non simmetrica (cristallo piezoelettrico)

Spostamenti atomici di 0.1 Å.



Monocristalli

QUARZO (SiO_2)

T_c = 573 °C

Molto stabile con la temperatura però presenta bassi coefficienti elettromeccanici e piezoelettrici.

Applicazioni: accelerometri e risonatori ($Q_m=10^6$)

NIOBATO DI LITIO ($LiNbO_3$)

T_c= 1140 °C

Ottime proprietà piezoelettriche a T_{amb} ma non ad alta temperatura. Ottime proprietà elettro-ottiche

Applicazioni: filtri SAW (Dispositivi di questo tipo sono utilizzati come filtri, oscillatori e trasformatori basati sulla trasduzione di onde acustiche).

Ceramici piezoelettrici

Classificazione dei PZT

➢ **Hard PZT** (PZT ad alta potenza)

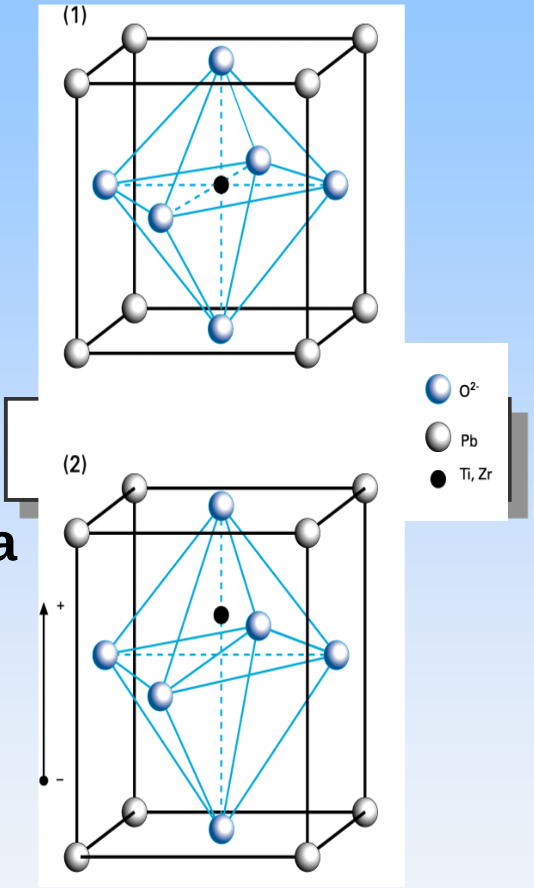
Bassa isteresi, alti Q_m, resistono ad alti carichi meccanici ed elettrici, invecchiano più lentamente.

Applicazioni: generatori e trasduttori ad elevata tensione elettrica o ad elevata potenza.

➢ **Soft PZT** (PZT ad alta sensibilità)

Grandi costanti dielettriche ma facile depolarizzazione e autoriscaldamento.

Applicazioni: sensori e traduttori ad alta impedenza.



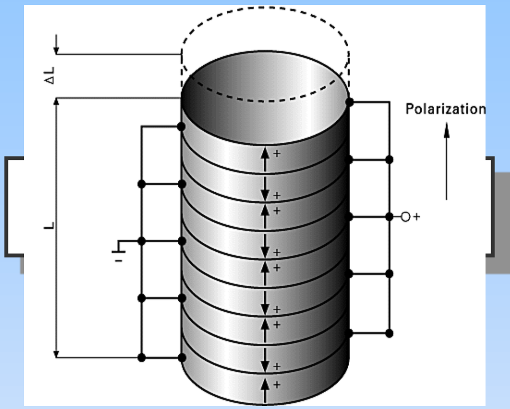
Applicazioni

Sensori: sfruttano l'effetto piezogeneratore

Attuatori: sfruttano l'effetto piezomotore

CAMPO	APPLICAZIONE
Automobilistico	Sensore di air bag, atomizzatori di combustibile (iniettori piezo), sensori di knocking, filtri radio, ecc.
Computer	Drive dell'hard disk, tastiera, stampanti a getto d'inchiostro, ecc.
Beni di consumo	Accendini del grill, umidificatori, rivelatori di fumo, pulitori di gioielli e lenti a contatto,
Industriale	Accelerometri, rivelatori di inquinamento, flussimetri, rivelatori di bolle d'aria nei tubi, sensori di impatto, indicatori di livello, equipaggiamento di microposizionamento, sensori di pressione, controlli non distruttivi, pulitori ad ultrasuoni, sgrassatori ad ultrasuoni, rettificatrici ad ultrasuoni, saldatori ad ultrasuoni, ecc.
Medico	Equipaggiamenti ecografici, pulitori dentali, nebulizzatori, terapie ad ultrasuoni, ecc.
Militare	Balistica, sonar, sistemi guida, ecc.
Telecomunicazioni, ottica e acustica	Microfoni, altoparlanti, tweeter, risonatori, filtri, microscopia a scansione, videocamere, ecc.

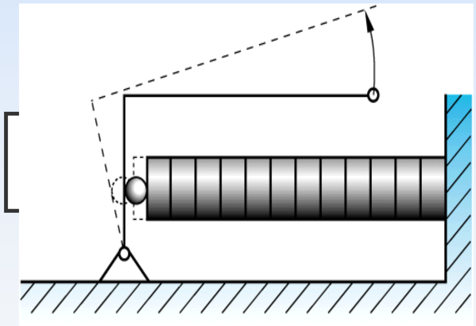
Attuatori piezoelettrici



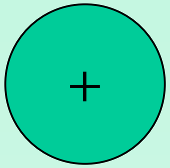
Attuatori in grado di generare uno spostamento anche micrometrico tramite la deformazione nel senso dello spessore che essi subiscono quando sono soggetti a campo elettrico.
L'impilaggio di strati sottili di ceramico connessi in parallelo determina una struttura multistrato in grado di generare grandi deformazioni a tensioni relativamente basse.

Applicazioni:

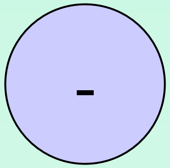
- *ottica*: stabilizzazione di immagine, microscopia a scansione, allineamento di fibre ottiche, posizionamento di specchi,ecc;
- *meccanica di precisione*: annullamento di vibrazioni, micropompe, attuazione di valvole, videocamere, stampanti ink-jet,ecc;
- *microelettronica*



A method for predicting the behavior of a crystal: The unit cell



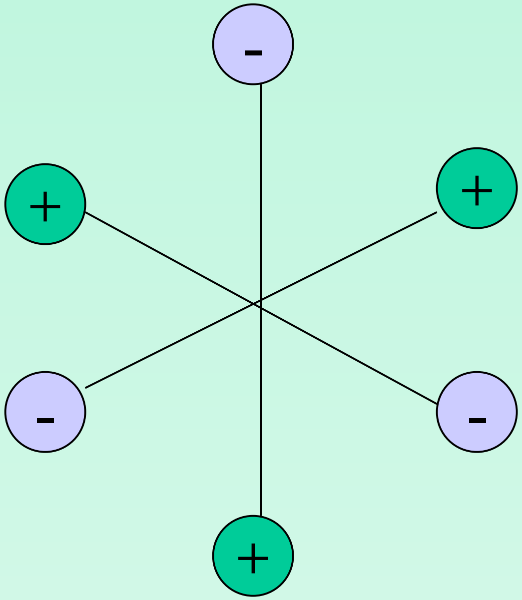
Represents silicon atom



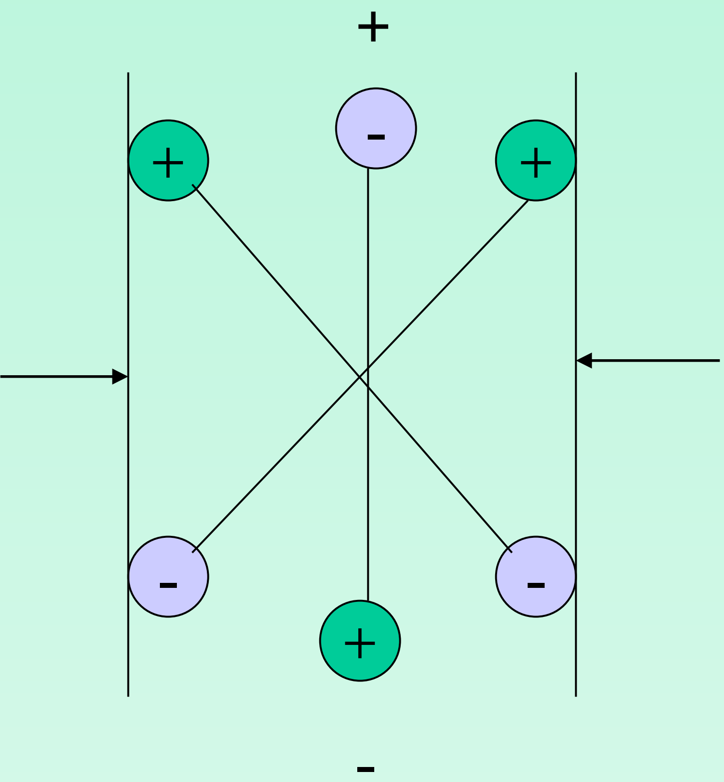
Represents oxygen atom

Not actually correct, but this method allows a good understanding of quartz crystals

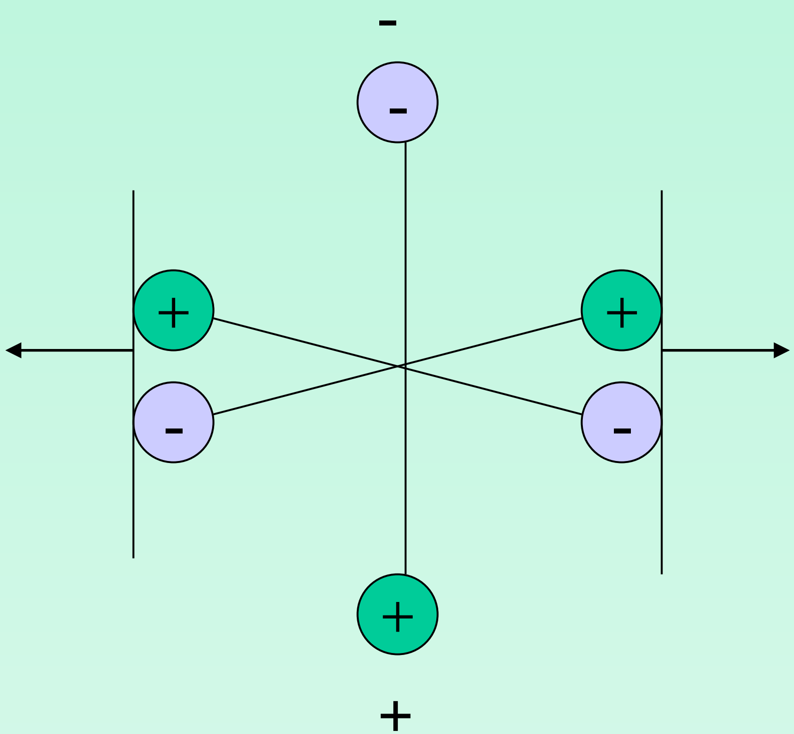
The unit cell of crystal silicon dioxide



A pushing force:
(aka: compression)

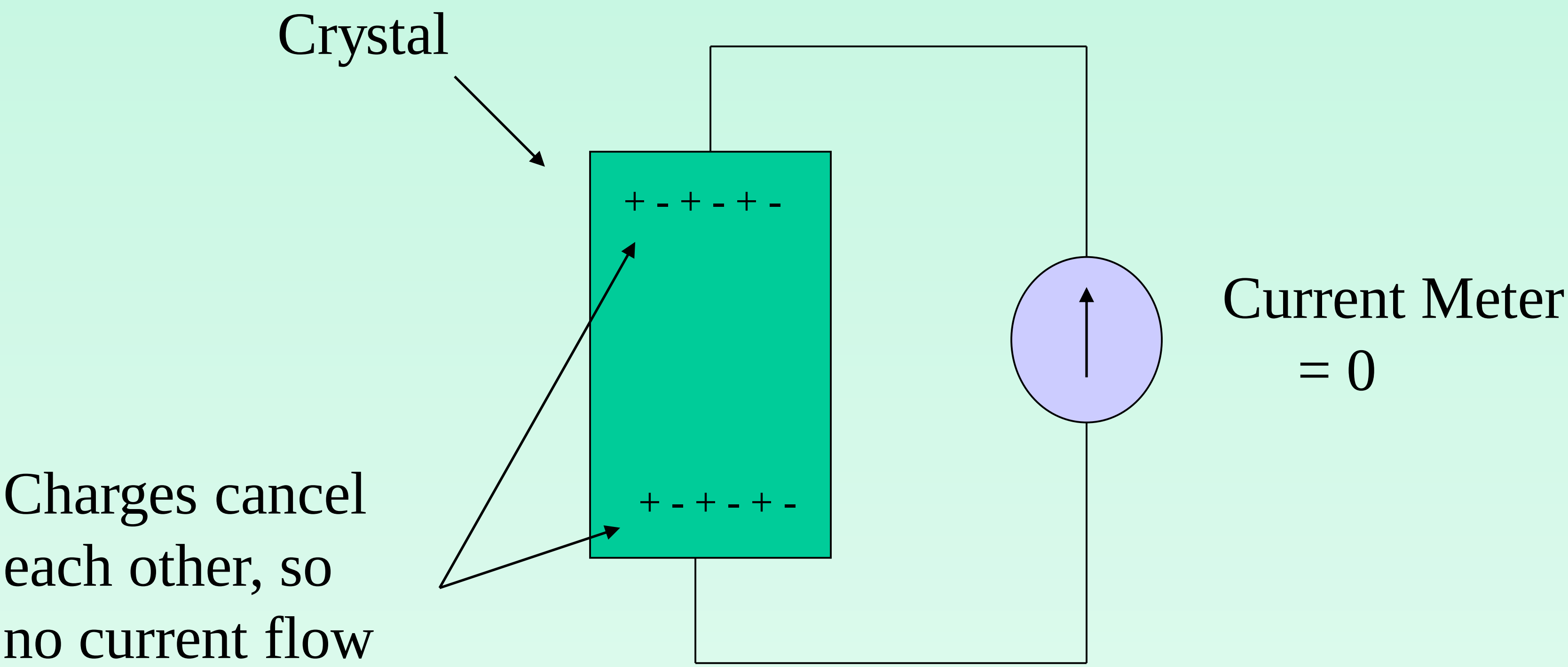


A pulling force:
(aka: tension)



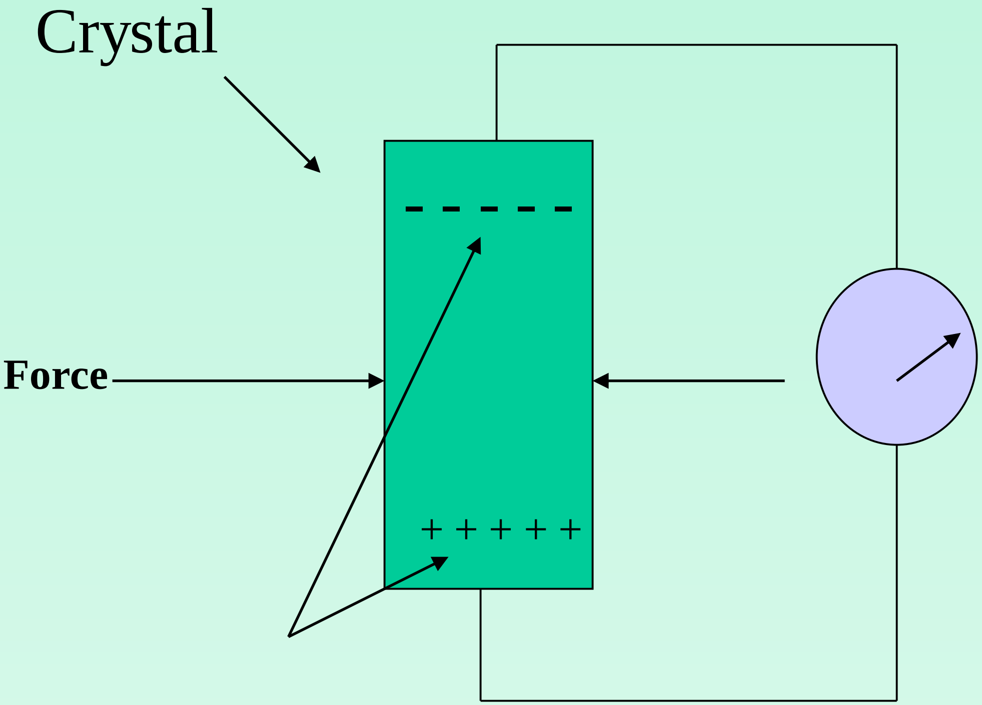
The Piezoelectric Effect

Crystal material at rest: No forces applied, so net current flow is 0



The Piezoelectric Effect

Crystal material with forces applied in direction of arrows………..



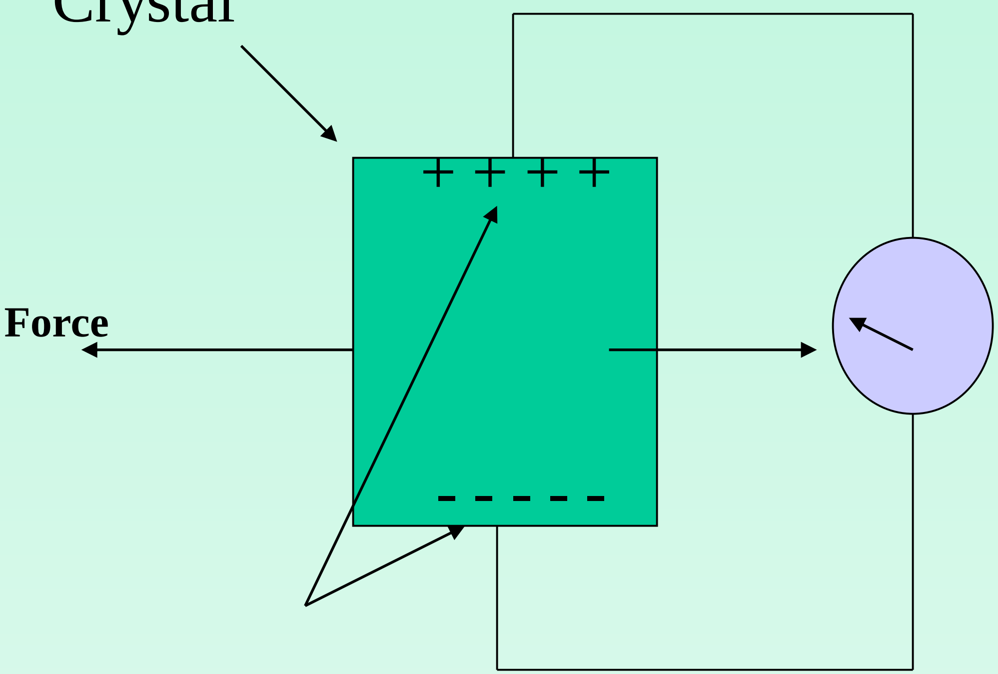
Current Meter deflects in + direction

Due to properties of symmetry, charges are net + on one side & net - on the opposite side: crystal gets thinner and longer

The Piezoelectric Effect

Changing the direction of the applied force………..

Crystal



Current Meter
deflects in -
direction

…. Changes the direction of current flow, and the crystal gets shorter and fatter.

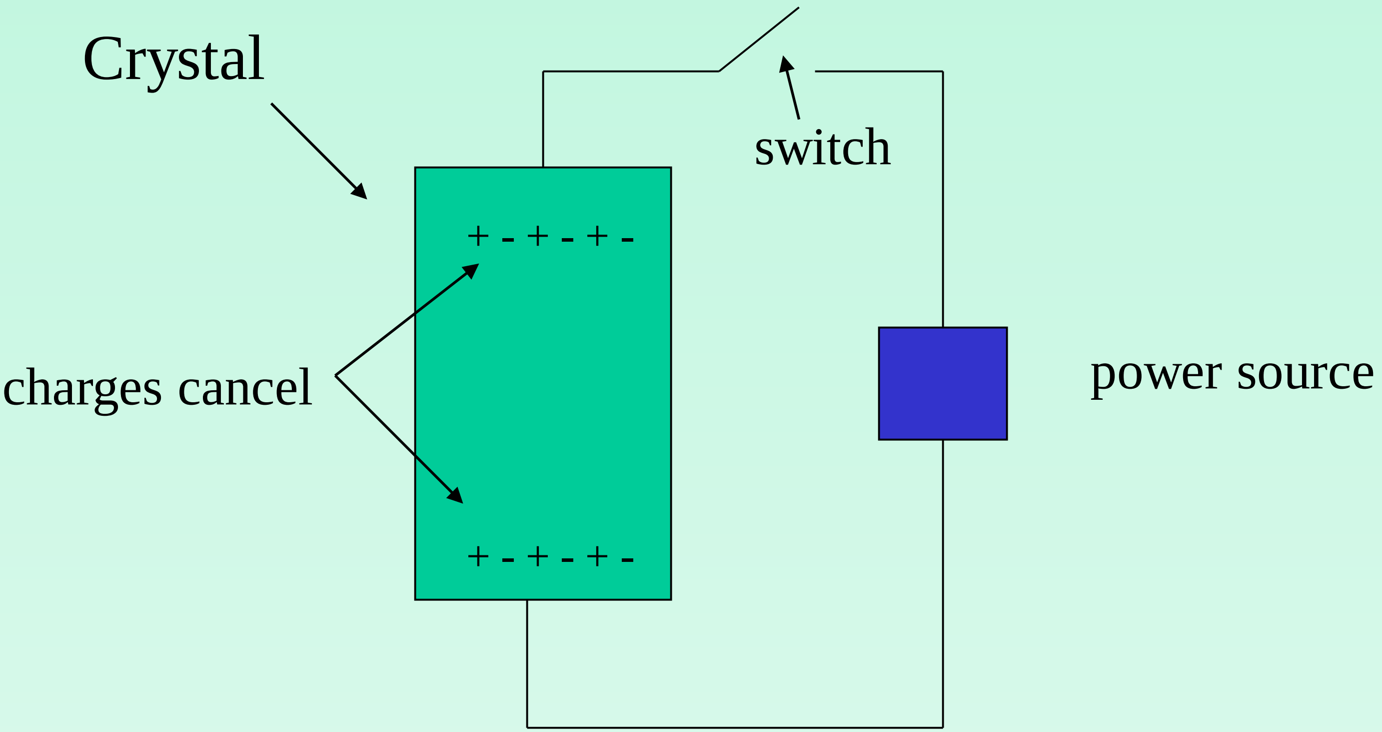
The electromechanical nature of piezoelectric material

- In general, if you deform a piezo crystal by applying a force, you will get charge separation: Think of a simple battery.

- Taking it one step further, what would happen to the crystal if you applied an electrical force that results in the exact same current flow from the proceeding circuit?

The electromechanical effect

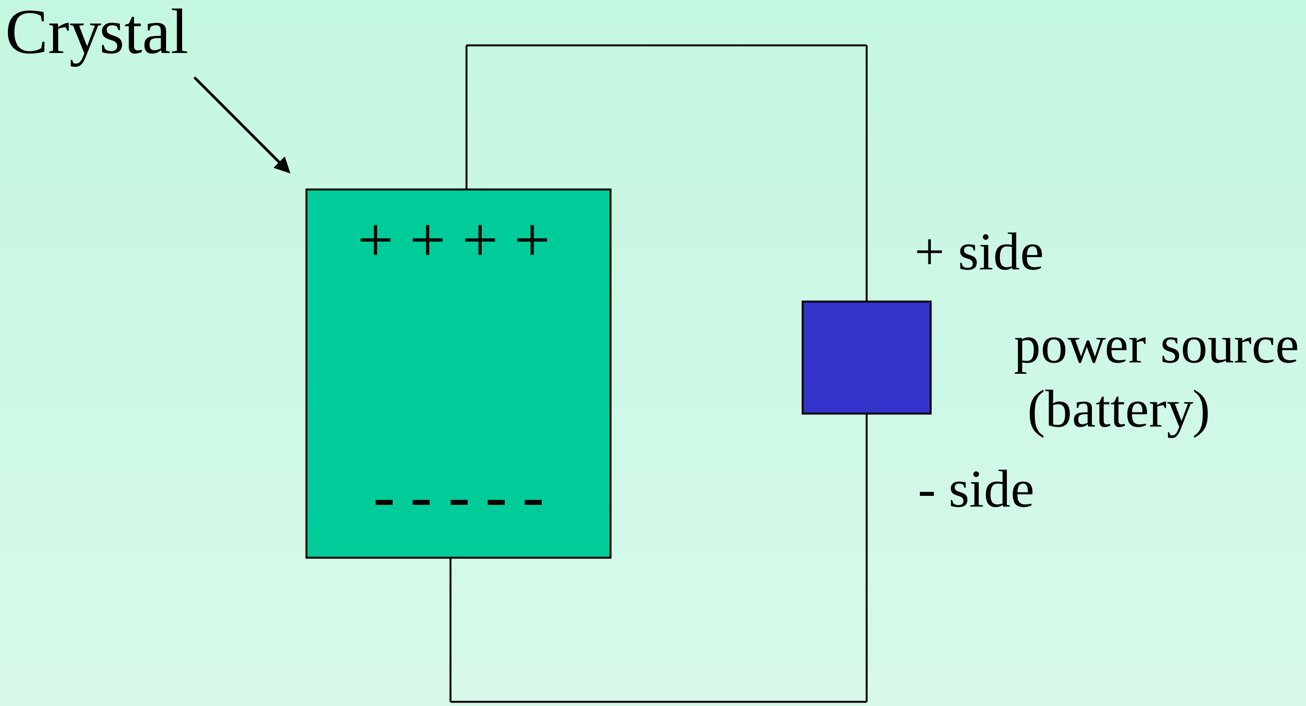
Now, replace the current meter with a power source capable of supplying the same current indicated by the meter….



…. With the switch open, the crystal material is now at rest again: the positive charges cancel the negative charges.

The electromechanical effect

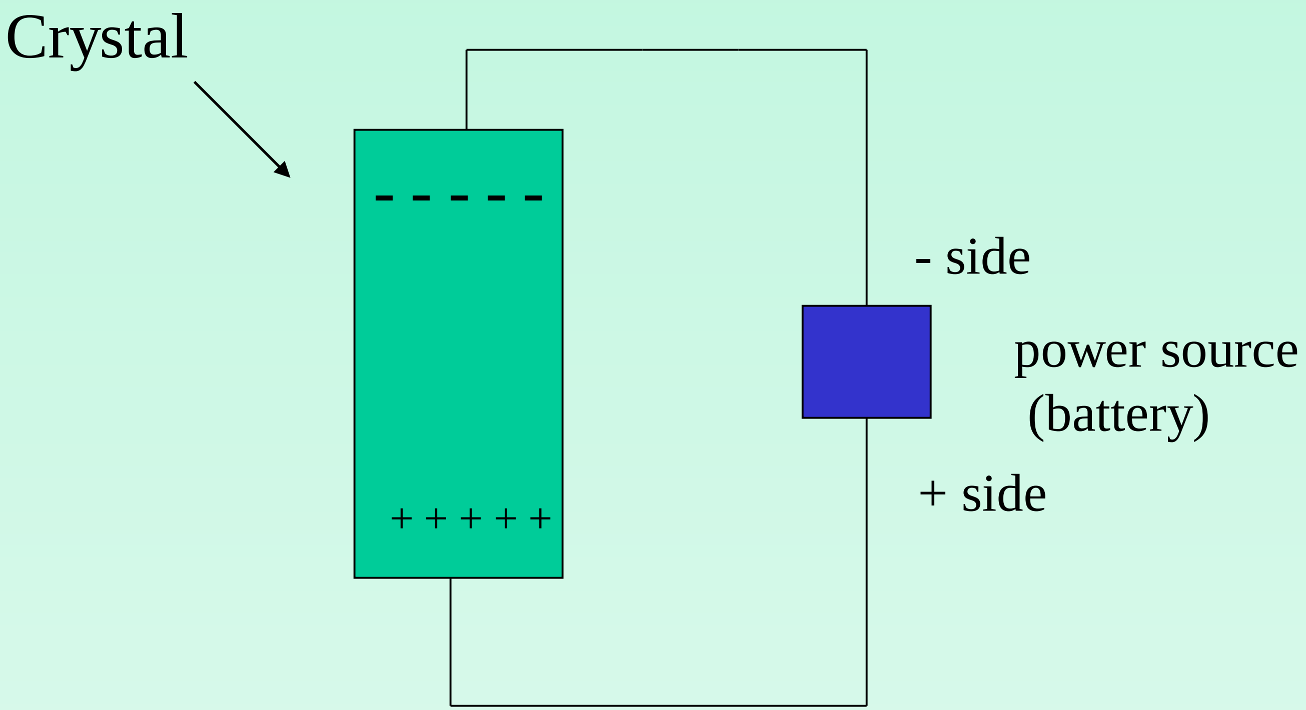
When the switch is closed, and you apply the exact amount of power to get the same current that resulted when you squeezed the crystal, the crystal should deform by the same amount!!



…. and, the crystal should get shorter and fatter.

The electromechanical effect

What will happen if you switched the battery around??

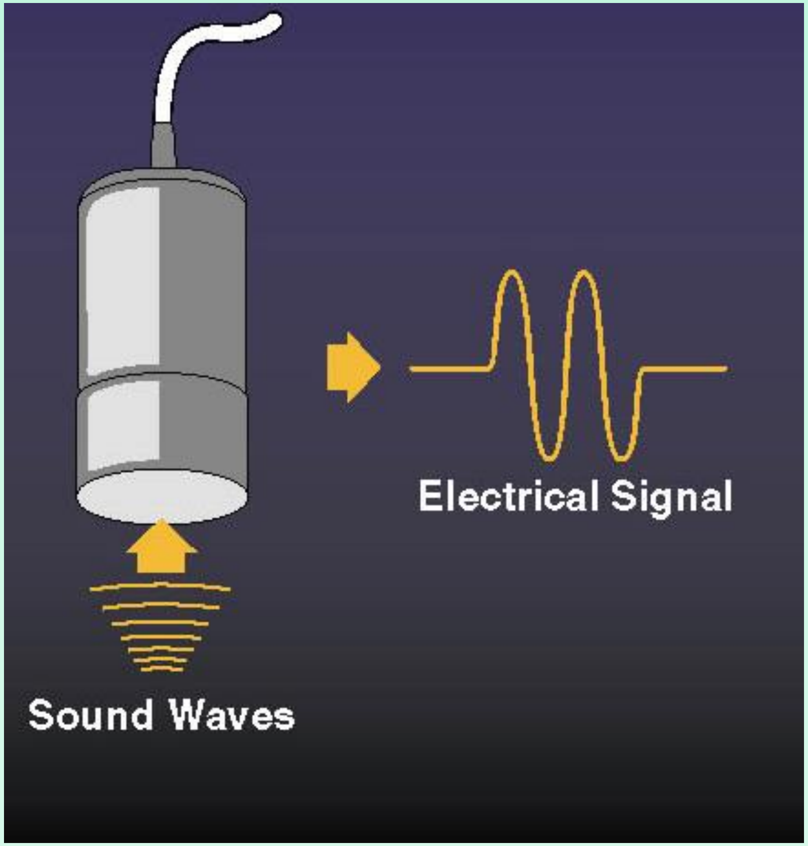


…. the crystal should get longer and skinnier.

Summary of the Piezoelectric & Electromechanical Effect

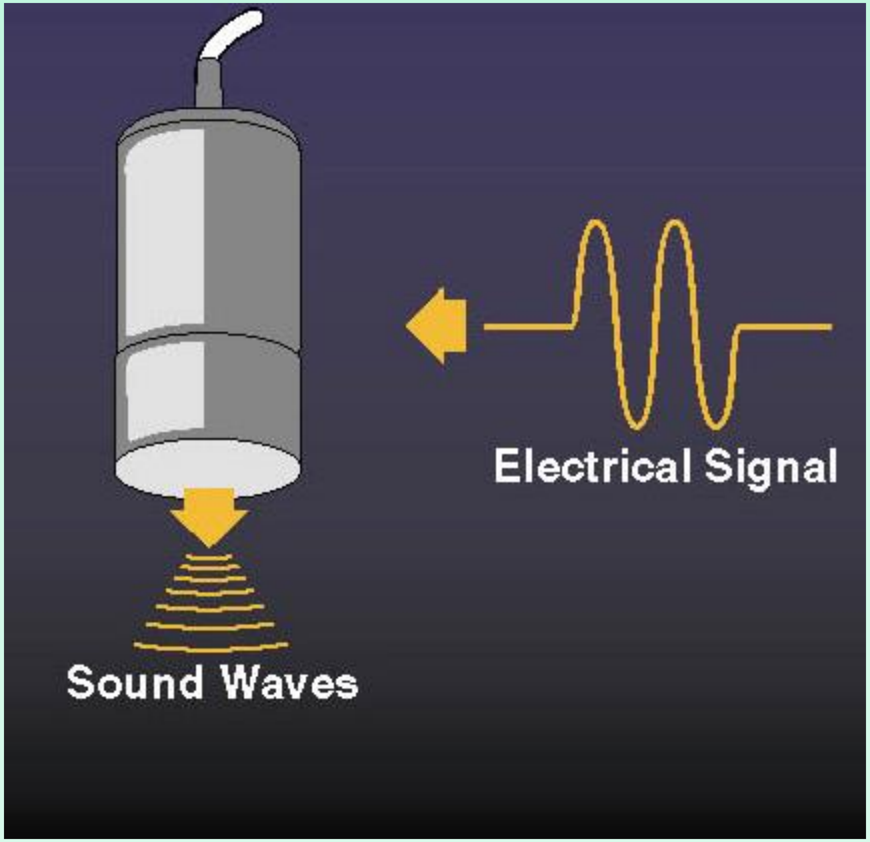
- A deformation of the crystal structure (eg: squeezing it) will result in an electrical current.
- Changing the direction of deformation (eg: pulling it) will reverse the direction of the current.
- If the crystal structure is placed into an electrical field, it will deform by an amount proportional to the strength of the field.
- If the same structure is placed into an electrical field with the direction of the field reversed, the deformation will be opposite.

Piezoelectric Effect



- Sound waves striking a PZ material produce an electrical signal
- Can be used to detect sound (and echoes)!

Reverse Piezoelectric Effect



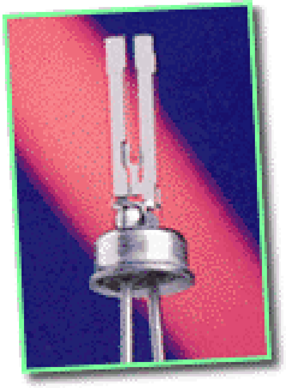
- Applying an electrical signal causes the PZ element to vibrate
- Produces a sound wave

Transducer

- Define?
- Many types of transducers exist
  - Pressure transducers
  - Air flow transducers, etc.
- What is function of transducer? convert electrical signals to sound waves, and vice versa.

Ultrasound Transducer Materials

- Quartz (naturally piezoelectric)
  - First used as a stable resonator in time measurement devices
  - Used in some laboratory ultrasound applications
- Most current applications use piezoelectric ceramics (ie, lead zirconate titanate; barium titanate)
  - Lower "Q" (good for short pulses)
  - Good sensitivity
  - Many shapes are possible



Miniature quartz tuning fork; 32,768 Hz.

Electronics Applications of Quartz Crystals

Military & Aerospace

Communications
Navigation
IFF
Radar
Sensors
Guidance systems
Fuzes
Electronic warfare
Sonobouys

Research & Metrology

Atomic clocks
Instruments
Astronomy & geodesy
Space tracking
Celestial navigation

Industrial

Communications
Telecommunications
Mobile/cellular/portable radio, telephone & pager
Aviation
Marine
Navigation
Instrumentation
Computers
Digital systems
CRT displays
Disk drives
Modems
Tagging/identification
Utilities
Sensors

Consumer

Watches & clocks
Cellular & cordless phones, pagers
Radio & hi-fi equipment
Color TV
Cable TV systems
Home computers
VCR & video camera
CB & amateur radio
Toys & games
Pacemakers
Other medical devices

Automotive

Engine control, stereo, clock
Trip computer, GPS

Quartz for the National Defense Stockpile, Report of the Committee on Cultured Quartz for the National Defense Stockpile, National Materials Advisory Board Commission on Engineering and Technical Systems, National Research Council, NMAB-424, National Academy Press, Washington, D.C., 1985.

Frequency Control Device Market

(as of ~2001)

Technology	Units per year	Unit price, typical	Worldwide market, $/year
Quartz Crystal	~ 2×10^9	~$1 ($0.1 to 3,000)	~$1.2B
Atomic Frequency Standards (see chapter 6)			
Hydrogen maser	~ 10	$200,000	$2M
Cesium beam frequency standard	~ 500	$50,000	$25M
Rubidium cell frequency standard	~ 60,000	$2,000	$120M

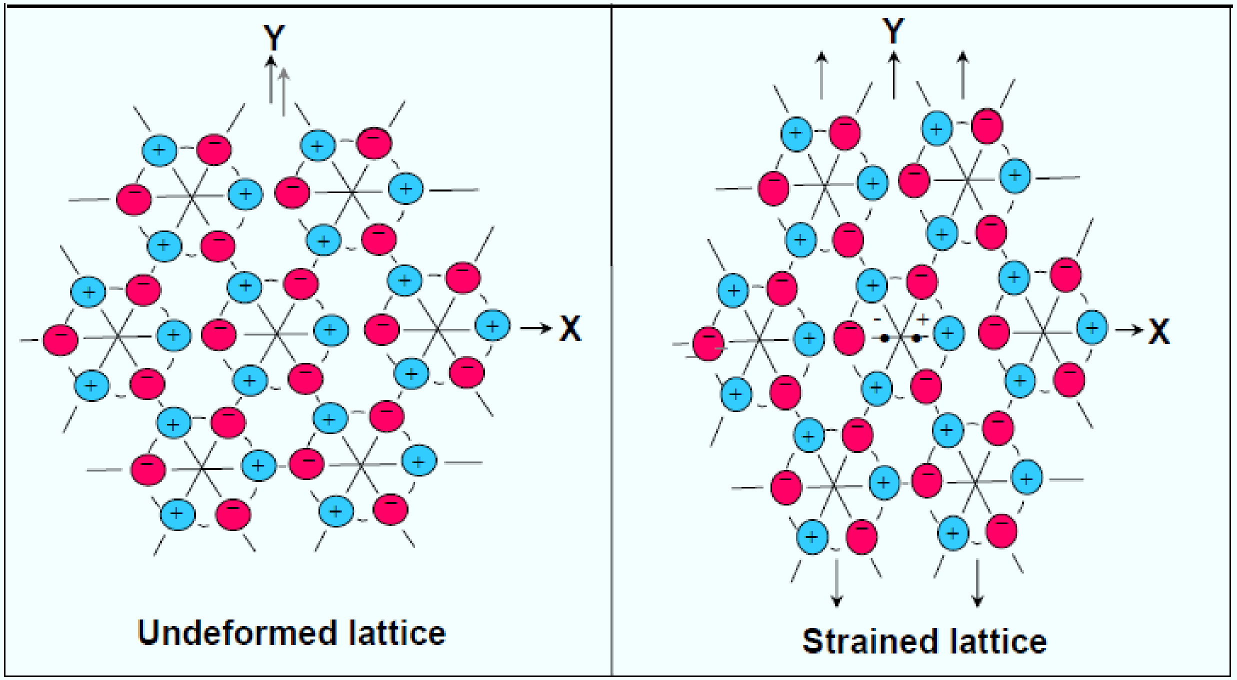
The units per year are estimates based on informal surveys of industry leaders. The numbers are probably accurate to better than a factor of two.

Why Quartz?

Quartz is the only material known that possesses the following combination of properties:

- Piezoelectric ("pressure-electric"; piezein = to press, in Greek)
- Zero temperature coefficient cuts exist
- Stress compensated cut exists
- Low loss (i.e., high Q)
- Easy to process; low solubility in everything, under "normal" conditions, except the fluoride and hot alkali etchants; hard but not brittle
- Abundant in nature; easy to grow in large quantities, at low cost, and with relatively high purity and perfection. Of the man-grown single crystals, quartz, at ~3,000 tons per year, is second only to silicon in quantity grown (3 to 4 times as much Si is grown annually, as of 1997).

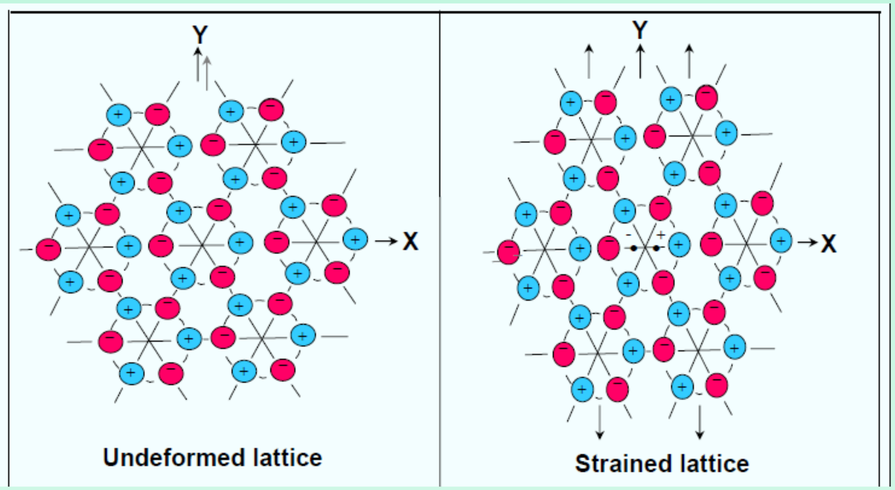
The Piezoelectric Effect



The piezoelectric effect provides a coupling between the mechanical properties of a piezoelectric crystal and an electrical circuit.

The direct piezoelectric effect was discovered by the Curie brothers in 1880. They showed that when a weight was placed on a quartz crystal, charges appeared on the crystal surface; the magnitude of the charge was proportional to the weight. In 1881, the converse piezoelectric effect was illustrated; when a voltage was applied to the crystal, the crystal deformed due to the lattice strains caused by the effect. The strain reversed when the voltage was reversed. The piezoelectric

Of the 32 crystal classes, 20 exhibit the piezoelectric effect (but only a few of these are useful). Piezoelectric crystals lack a center of symmetry. When a force deforms the lattice, the centers of gravity of the positive and negative charges in the crystal can be separated so as to produce surface charges. The figure shows one example (from Kelvin's qualitative model) of the effect in quartz. Each silicon atom is represented by a plus, and each oxygen atom by a minus. When a strain is applied so as to elongate the crystal along the Y-axis, there are net movements of negative charges to the left and positive charges to the right (along the X-axis).

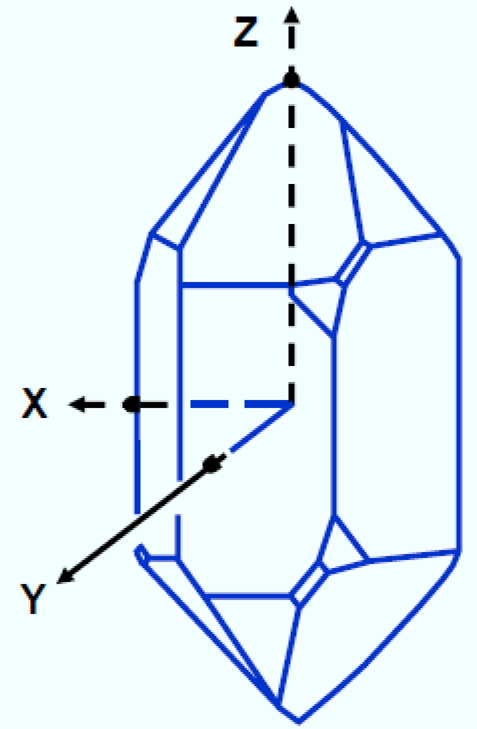


Piezoelectricity is a linear effect. Reversal of the electric field reverses the strain, i.e., the mechanical deformation.

The electromechanical (also called piezoelectric) coupling factor k is an important characteristic of a piezoelectric material; k is between zero and one and is dimensionless, e.g., k = 8.8% for AT-cut quartz, and k = 4.99% for SC-cut quartz. It is a measure of the efficacy of piezoelectric transduction, and it is a determinant of important device characteristics such as filter bandwidth, insertion loss, and the location and spacings of resonators' critical frequencies (e.g., the series resonance to antiresonance frequency spacing).

The Piezoelectric Effect in Quartz

STRAIN		FIELD along:		
		X	Y	Z
EXTENSIONAL along:	X	√		
	Y	√		
	Z			
SHEAR about:	X	√		
	Y		√	
	Z		√	



In quartz, the five strain components shown may be generated by an electric field. The modes shown on the next page may be excited by suitably placed and shaped electrodes. The shear strain about the Z-axis produced by the Y-component of the field is used in the rotated Y-cut family, including the AT, BT, and ST-cuts.

What is Q and Why is it Important?

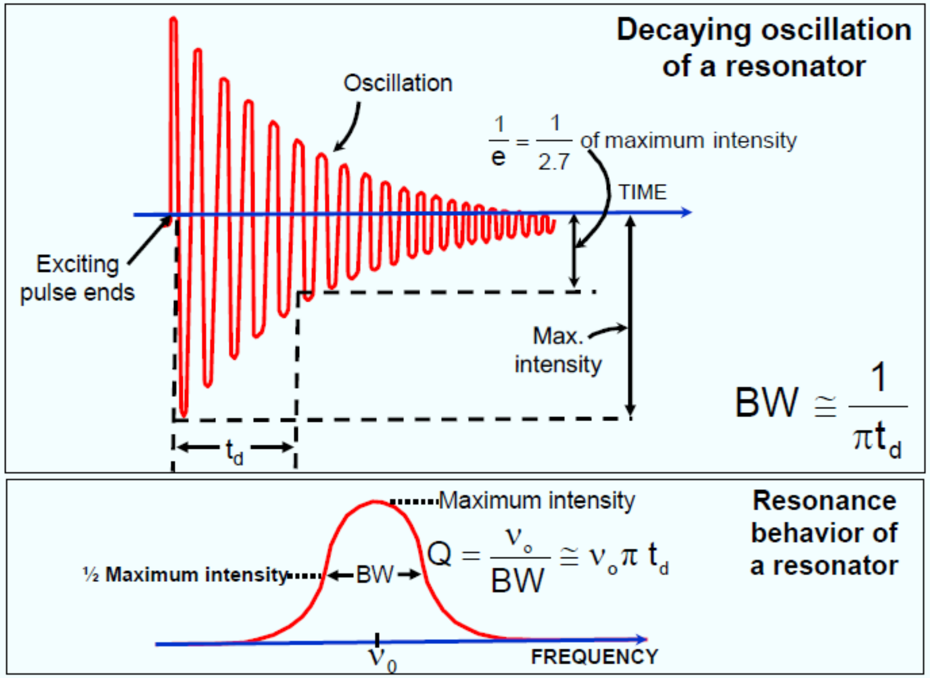
$$Q \equiv 2\pi \frac{\text{Energy stored during a cycle}}{\text{Energy dissipated per cycle}}$$

Q is proportional to the decay-time, and is inversely proportional to the linewidth of resonance (see next page).

- The higher the Q, the higher the frequency stability and accuracy **capability** of a resonator (i.e., high Q is a necessary but not a sufficient condition). If, e.g., Q = 10^6, then 10^{-10} accuracy requires ability to determine center of resonance curve to 0.01% of the linewidth, and stability (for some averaging time) of 10^{-12} requires ability to stay near peak of resonance curve to 10^{-6} of linewidth.

- Phase noise close to the carrier has an especially strong dependence on Q ($\mathcal{L}(f) \propto 1/Q^4$).

Decay Time, Linewidth, and Q



In addition to the definition on the previous page, equivalent definitions of Q are shown above. Q is the frequency divided by the bandwidth of resonance, and it also determines the rate at which a signal decays after the vibration excitation stops - the higher the Q, the narrower the bandwidth and the longer it takes for the excitation to decay. Q is proportional to the time it takes for the signal to decay to 1/e of the amplitude of vibration prior to the cessation of excitation. This relationship is used in one method (sometimes referred to as the "logarithmic decrement" method) of measuring Q.

The relationship between Q and decay time is also relevant to oscillator startup time. When an oscillator is turned on, it takes a finite amount of time for the oscillation to build up. The oscillator's startup time depends on the loaded Q of the resonator in the sustaining circuit, and the loop gain of the circuit.

Factors that Determine Resonator Q

The **maximum Q** of a resonator can be expressed as:

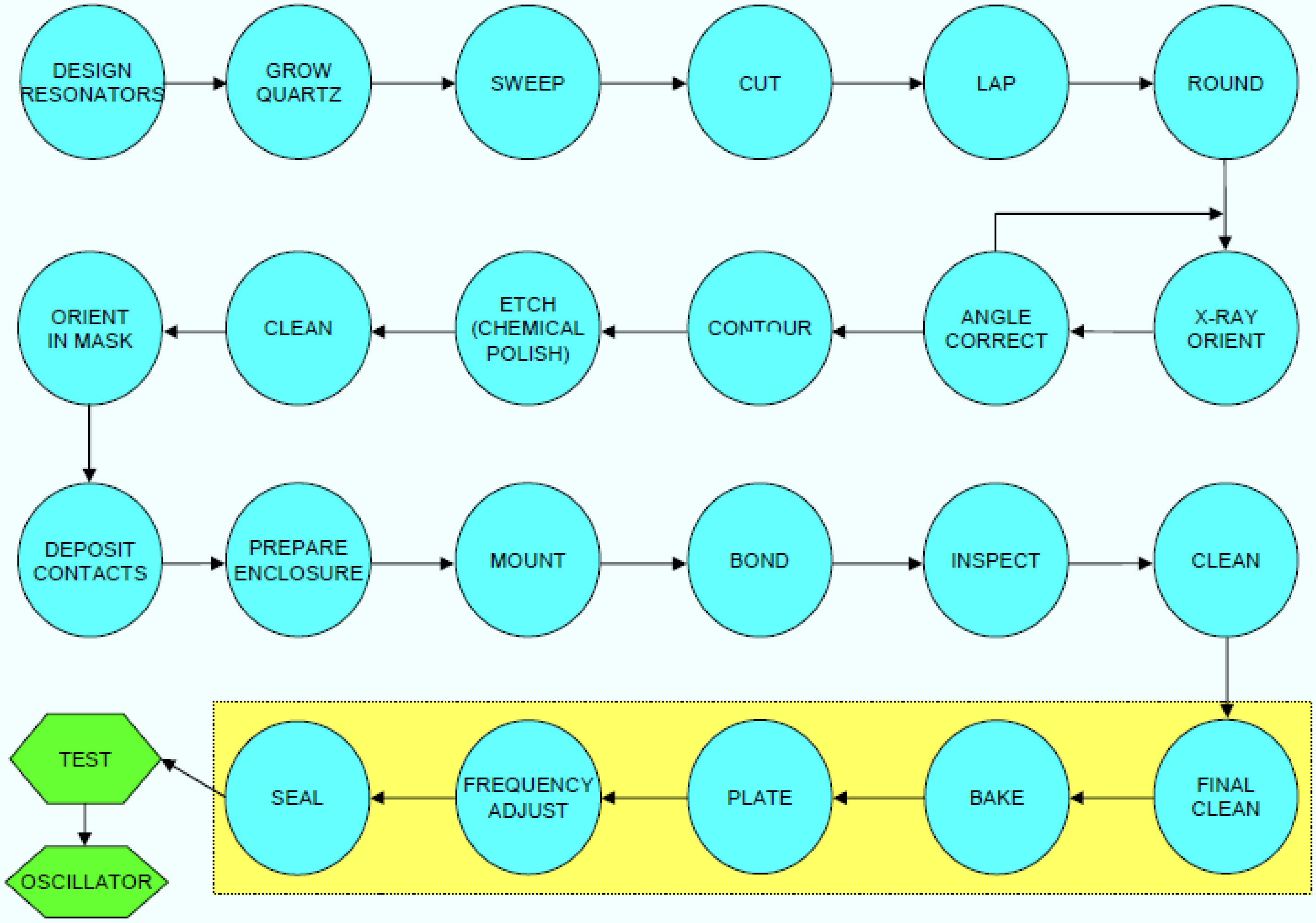
$$Q_{max} = \frac{1}{2\pi f \tau},$$

where f is the frequency in Hz, and τ is an empirically determined "motional time constant" in seconds, which varies with the angles of cut and the mode of vibration. For example, $\tau = 1 \times 10^{-14}$s for the AT-cut's c-mode (Q_{max} = 3.2 million at 5 MHz), $\tau = 9.9 \times 10^{-15}$s for the SC-cut's c-mode, and $\tau = 4.9 \times 10^{-15}$s for the BT-cut's b-mode.

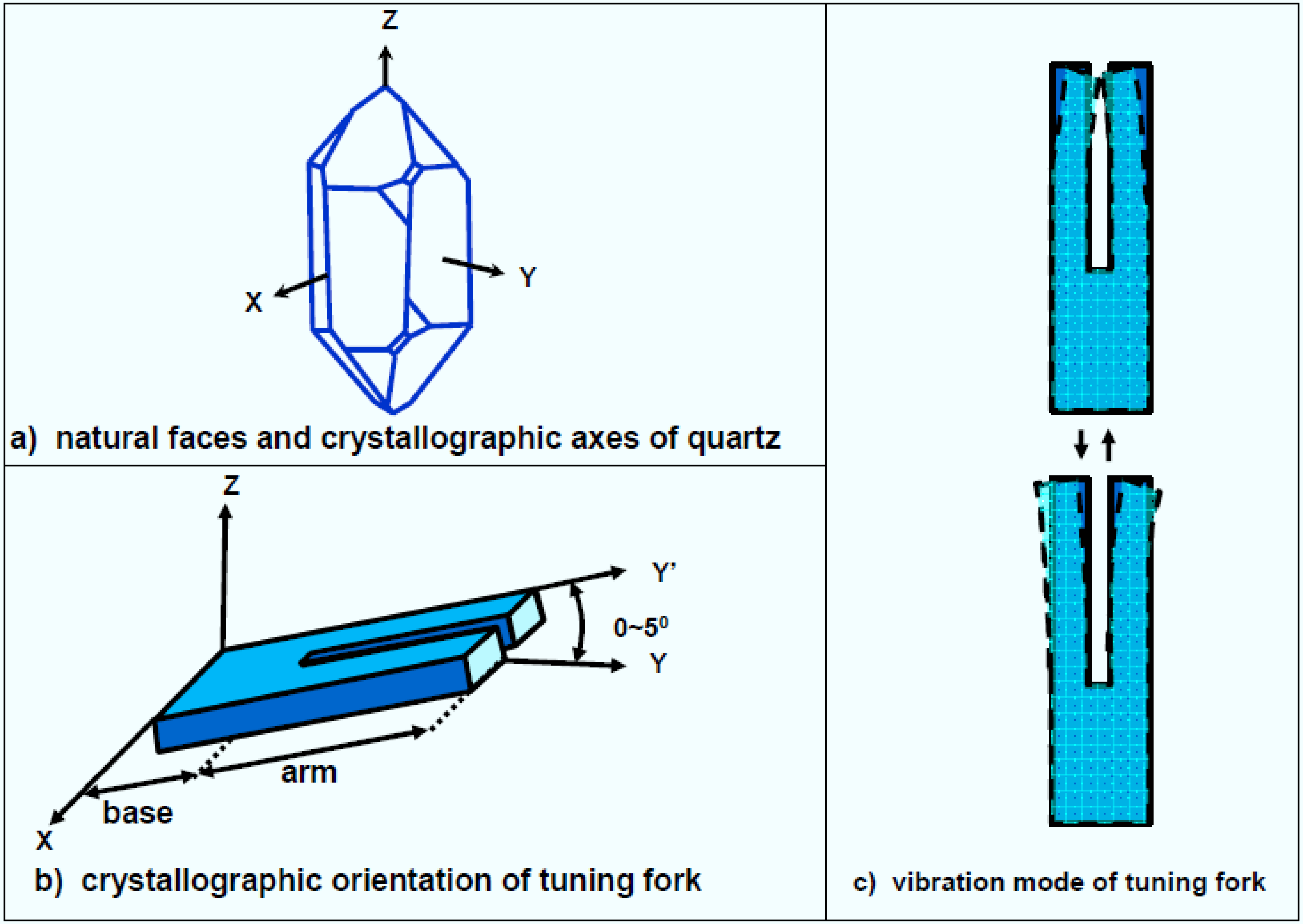
Other factors which affect the Q of a resonator include:

- Overtone
- Surface finish
- Material impurities and defects
- Mounting stresses
- Bonding stresses
- Temperature
- Electrode geometry and type
- Blank geometry (contour, dimensional ratios)
- Drive level
- Gases inside the enclosure (pressure, type of gas)
- Interfering modes
- Ionizing radiation

Resonator Fabrication Steps



Quartz Tuning Fork



a) natural faces and crystallographic axes of quartz

b) crystallographic orientation of tuning fork

c) vibration mode of tuning fork

Allan Deviation

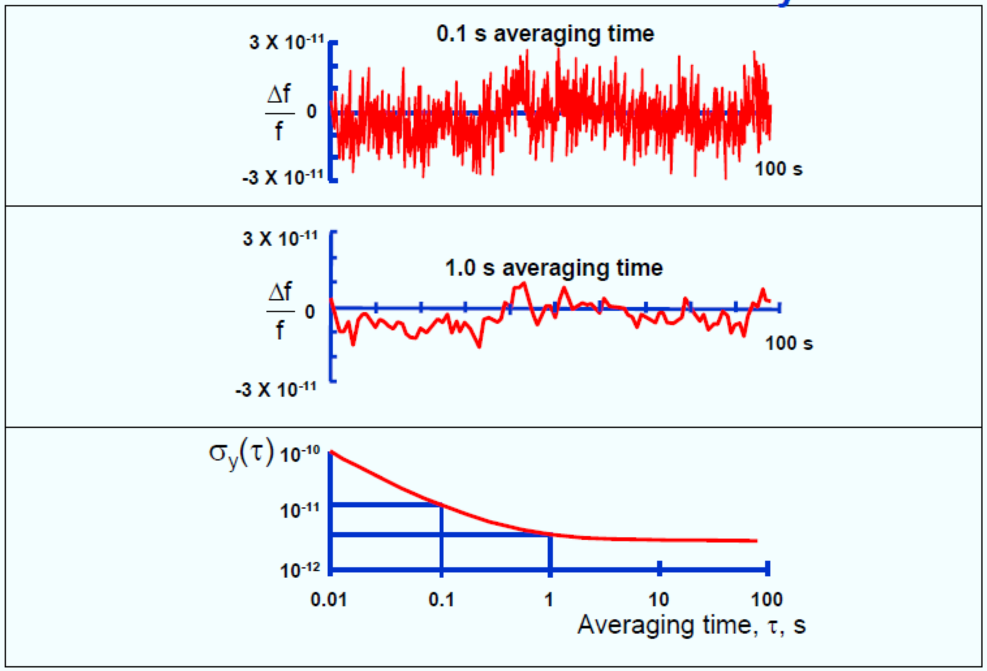
Also called **two-sample deviation,** or square-root of the "**Allan variance,**" it is the standard method of describing the short term stability of oscillators in the time domain. It is denoted by $\sigma_y(\tau)$,

where $$\sigma_y^2(\tau) = \frac{1}{2} < (y_{k+1} - y_k)^2 > .$$

The fractional frequencies, $y = \frac{\Delta f}{f}$ are measured over a time interval, τ; $(y_{k+1} - y_k)$ are the differences between pairs of successive measurements of y, and, ideally, < > denotes a time average of an infinite number of $(y_{k+1} - y_k)^2$. A good estimate can be obtained by a limited number, m, of measurements ($m \geq 100$). $\sigma_y(\tau)$ generally denotes $\sqrt{\sigma_y^2(\tau, m)}$, i.e.,

$$\sigma_y^2(\tau) = \sigma_y^2(\tau,m) = \frac{1}{m}\sum_{j=1}^{m}\frac{1}{2}\left(y_{k+1} - y_k\right)_j^2$$

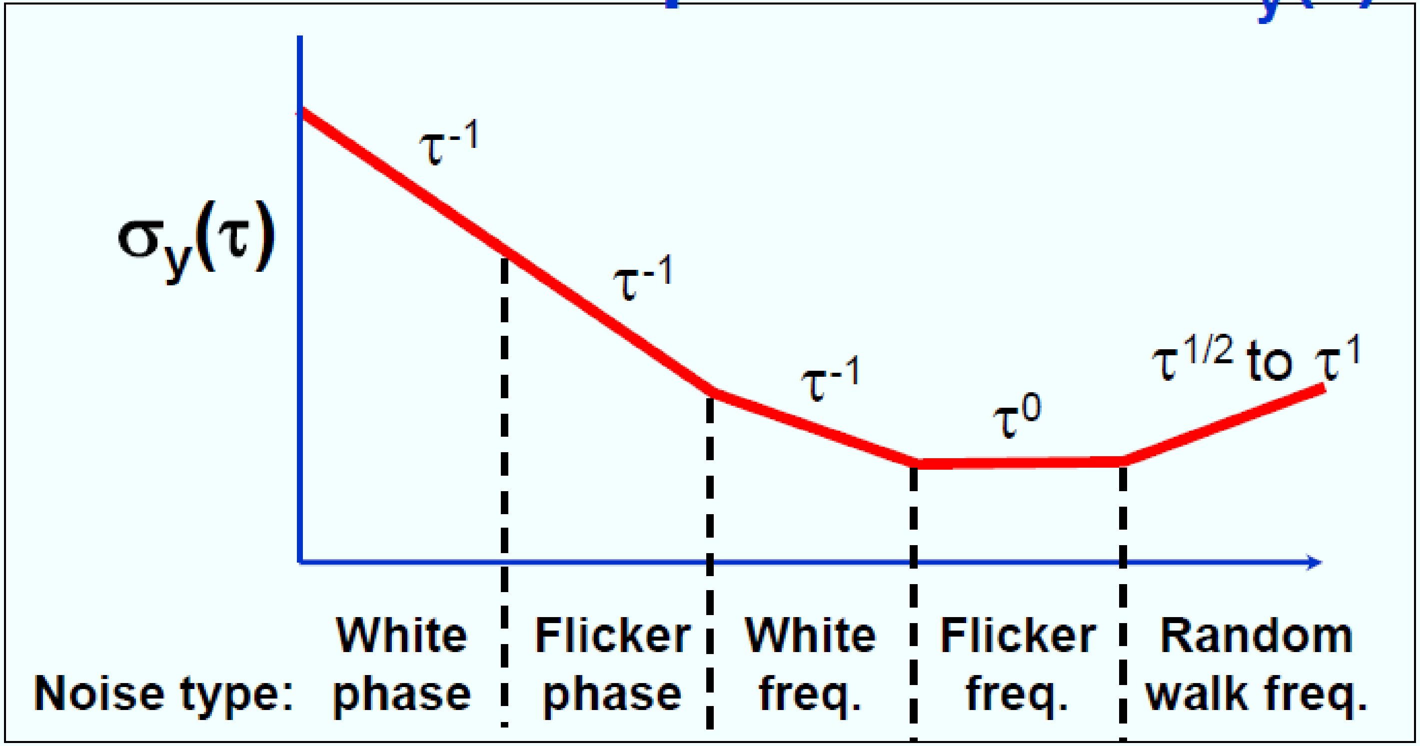
Frequency Noise and $\sigma_y(\tau)$



"The noise" is a function of the averaging time (also called "measurement time" or "tau"), as is illustrated above. For the same oscillator, the fluctuations in the frequency vs. time plot measured with a 0.1 second averaging time are larger than when measured with a 1 second averaging time. Also shown are the corresponding Allan deviations.

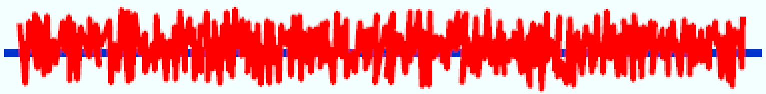
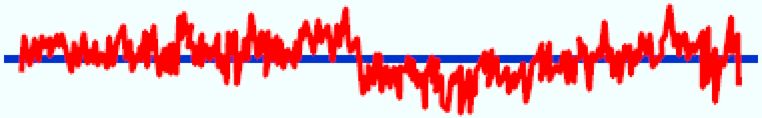
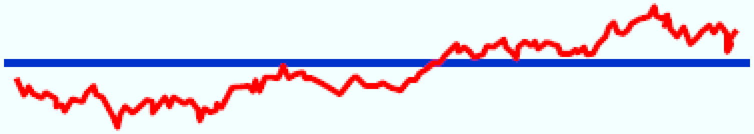
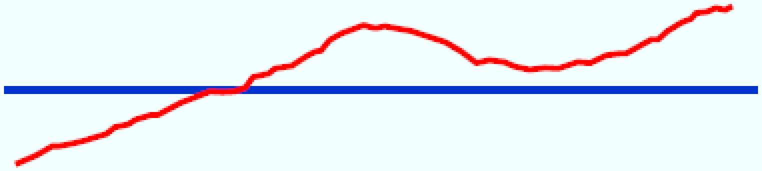
At short averaging times, the longer the averaging time, the lower the noise, up to the "flicker floor," i.e., for certain noise processes (see the next four pages), the hills and valleys in the frequency vs. time data average out. Longer averaging does not help when the dominant noise process is flicker of frequency. At the flicker floor, the Allan deviation is independent of averaging time. At longer averaging times, the Allan deviation increases because the dominant noise process is random walk of frequency, for which the longer the averaging time, the larger the Allan deviation.

Power Law Dependence of $\sigma_y(\tau)$



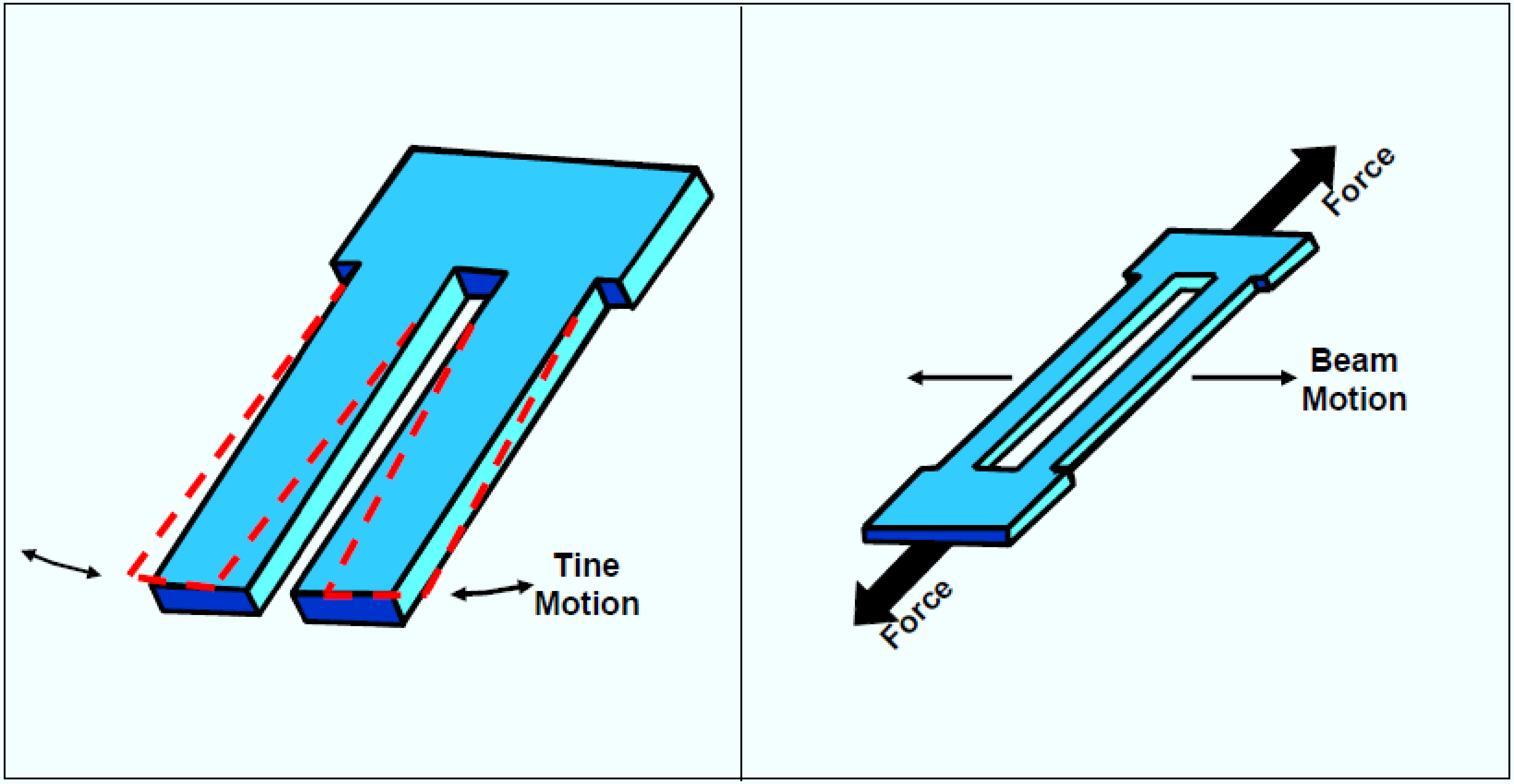
Below the flicker of frequency noise (i.e., the "flicker floor") region, crystal oscillators typically show τ^{-1} (white phase noise) dependence. Atomic standards show $\tau^{-1/2}$ (white frequency noise) dependence down to about the servo-loop time constant, and τ^{-1} dependence at less than that time constant. Typical τ's at the start of flicker floors are: 1s for a crystal oscillator, 10^3s for a Rb standard and 10^5s for a Cs standard. At large τ's, random walk of frequency and aging dominate.

Pictures of Noise

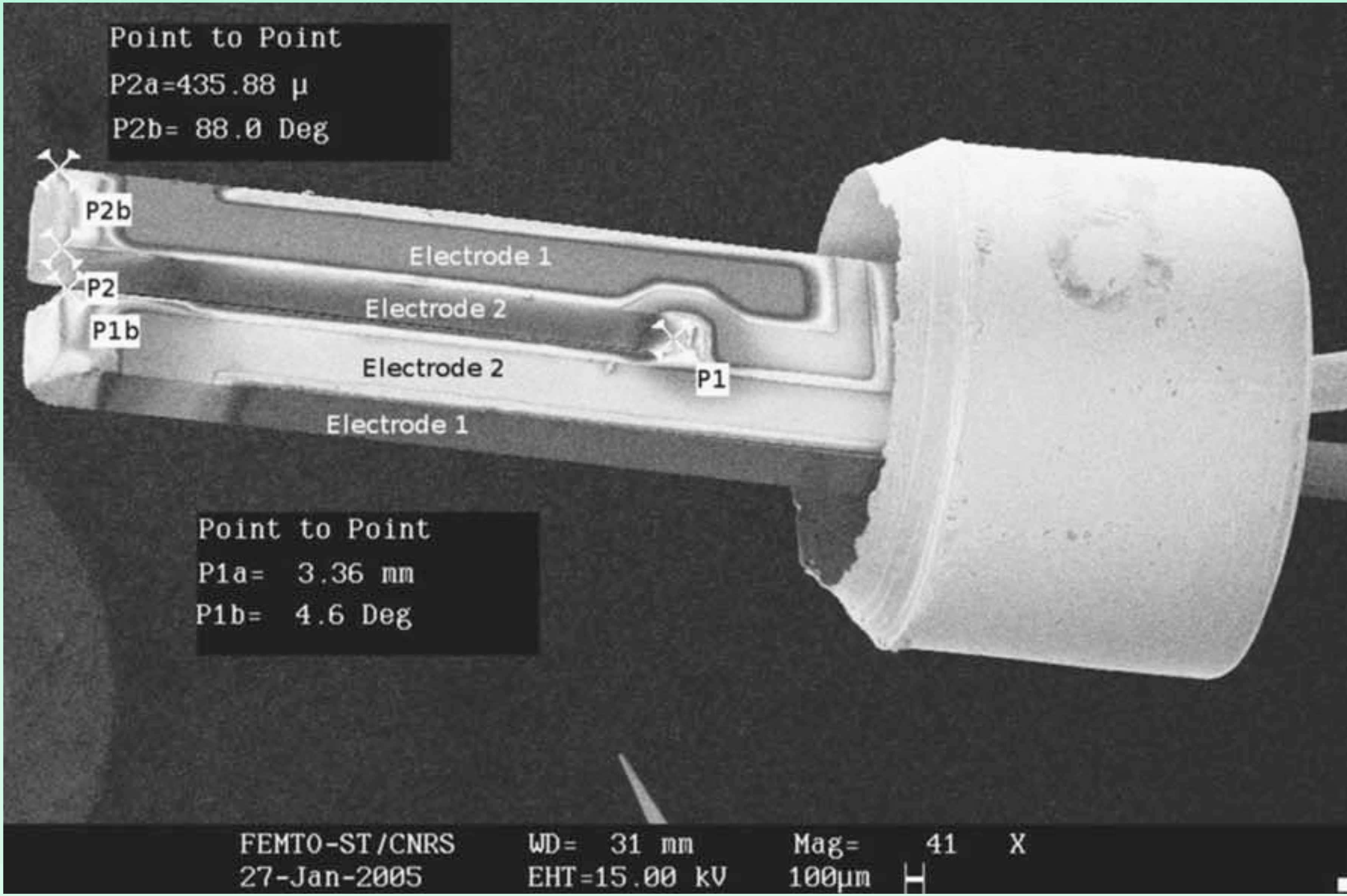
Plot of z(t) vs. t	$S_z(f) = h_\alpha f^\alpha$	Noise name
	$\alpha = 0$	White
	$\alpha = -1$	Flicker
	$\alpha = -2$	Random walk
	$\alpha = -3$	

Plots show fluctuations of a quantity **z**(t), which can be,e.g., the output of a counter (Δf vs. t) or of a phase detector (ϕ[t] vs. t). The plots show simulated time-domain behaviors corresponding to the most common (power-law) spectral densities; h_α is an amplitude coefficient. Note: since $S_{\Delta f} = f^2 S_\phi$, e.g. white frequency noise and random walk of phase are equivalent.

Tuning Fork Resonator Sensors



Photolithographically produced tuning forks, single- and double-ended (flexural-mode or torsional-mode), can provide low-cost, high-resolution sensors for measuring temperature, pressure, force, and acceleration. Shown are flexural-mode tuning forks.


Point to Point
P2a=435.88 µ
P2b= 88.0 Deg
P2b
P2
P1b
Electrode 1
Electrode 2
Electrode 2
Electrode 1
P1
Point to Point
P1a= 3.36 mm
P1b= 4.6 Deg
FEMTO-ST/CNRS
27-Jan-2005
WD= 31 mm
EHT=15.00 kV
Mag= 41 X
100µm

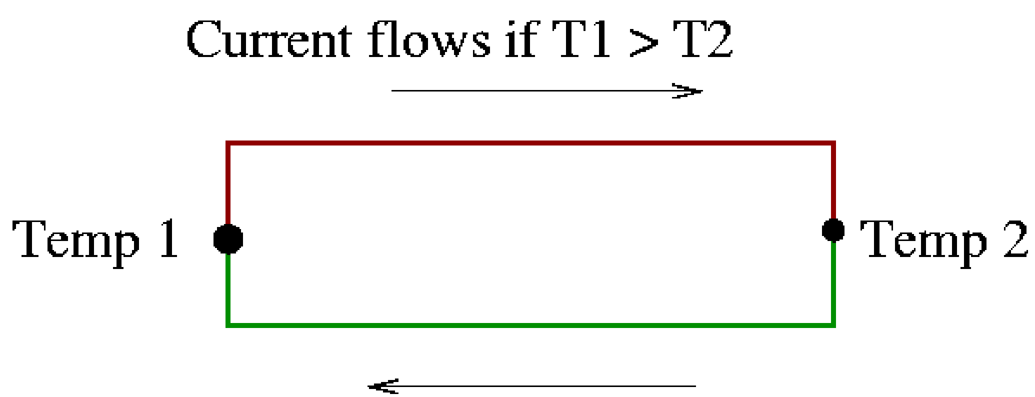
Seebeck and Peltier Effects.

Seebeck effect: Thermally induced electric currents in circuits of dissimilar material.

Peltier effect: absorption of heat when an electric current cross a junction two dissimilar materials

The dissimilar materials can be different species, or the the same species in different strain states.

The Peltier effect can be thought of as the reverse of the Seebeck effect



Seebeck effect

Free electrons act as a gas. If a metal rod is hot at one end and cold at the other, electrons flow from hot to cold.

So a temperature gradient leads to a voltage gradient:

$$\frac{dV}{dx} = \alpha \frac{dT}{dx}$$

Where α is the absolute Seebeck coefficient of the material.

When two materials with different α coefficients are joined in a loop, then there is a mis-match between the temperature-induced voltage drops.

The differential Seebeck coefficient is: $\alpha_{AB} = \alpha_A - \alpha_B$

Thermocouples

The net voltage at the junction is $$dV_{AB} = \alpha_{AB} dT$$

So the differential Seebeck coefficient is also $$\alpha_{AB} = \frac{dV_{AB}}{dT}$$

This is the basis of the thermocouple sensor

Thermocouples are not necessarily linear in response.
E.g. the T – type thermocouple has characteristics

$$V = a_0 + a_1 T + a_2 T^2$$

Where the a's are material properties:

$$V = -0.0543 + 4.094 \times 10^{-2} T + 2.874 \times 10^{-5} T^2$$

The sensitivity is the differential Seebeck coefficient

$$\alpha_{AB} = \frac{dV_{AB}}{dT} = a_1 + 2a_2 T = 4.094\times10^{-2} + 5.748\times10^{-5} T$$

Independent of geometry, manufacture etc. Only a function of materials and temperature.

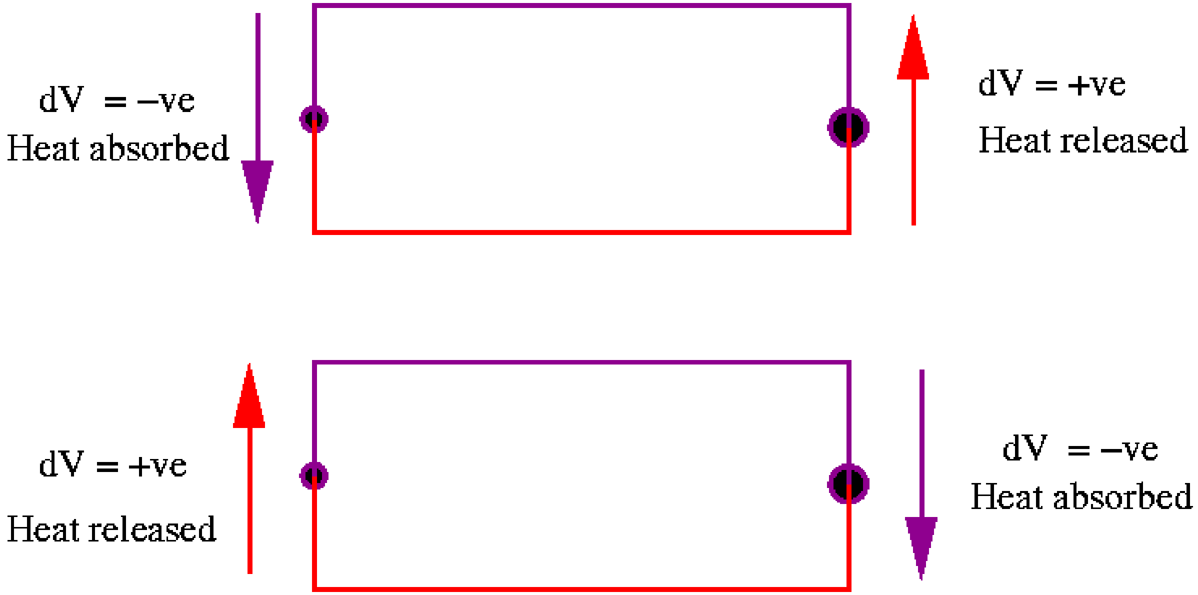
Seebeck effect is a transducer which converts thermal to electrical energy.

Can be used as solid state thermal to electrical energy converter (i.e. engine)as well as an accurate temperature sensor.

Seebeck engines are currently not very efficient but are much more reliable than heat engines. They are used by NASA for nuclear powered deep-space probes.

Peltier Effect.

If electric current is passed through a dissimilar material junction, then the heat may be generated or *absorbed*.



The change in heat dQ =±p I dt

(where p is the Peltier constant (unit of voltage))

Can be used to produce heat or *cold* as required.

Eg. Cooling high performance Microprocessors.

Table 3-8 Characteristics of some thermocouple types

Junction Materials	*Sensitivity* $\mu V/°C$ *(@ 25°C)*	*Temperature Range (°C)*	*Applications*	*Designation*
Copper/Constantan	40.9	-270 to +600	Oxidation, reducing, inert, vacuum. Preferred below 0°C. Moisture resistant	T
Iron/Constantan	51.7	-270 to +1000	Reducing and inert atmosphere. Avoid oxidation and moisture	J
Chromel/Alumel	40.6	-270 to 1300	Oxidation and inert atmospheres	K
Chromel/Constantan	60.9	-200 to 1000		E
Pt (10%)/Rh-Pt	6.0	0 to 1550	Oxidation and inert atmospheres, avoid reducing atmosphere and metallic vapors	S
Pt (13%)/Rh-Pt	6.0	0 to 1600	Oxidation and inert atmospheres, avoid reducing atmosphere and metallic vapors	R