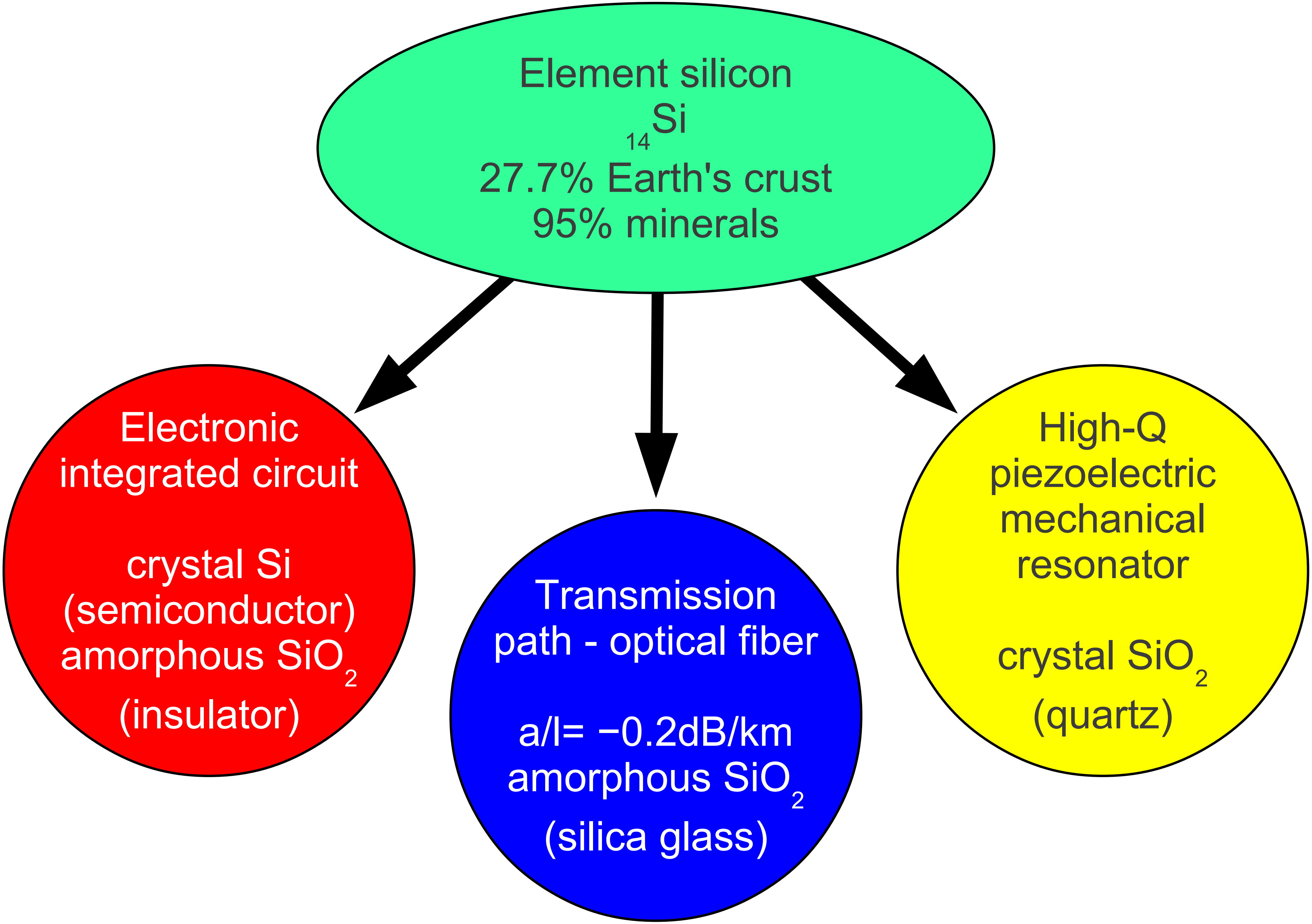
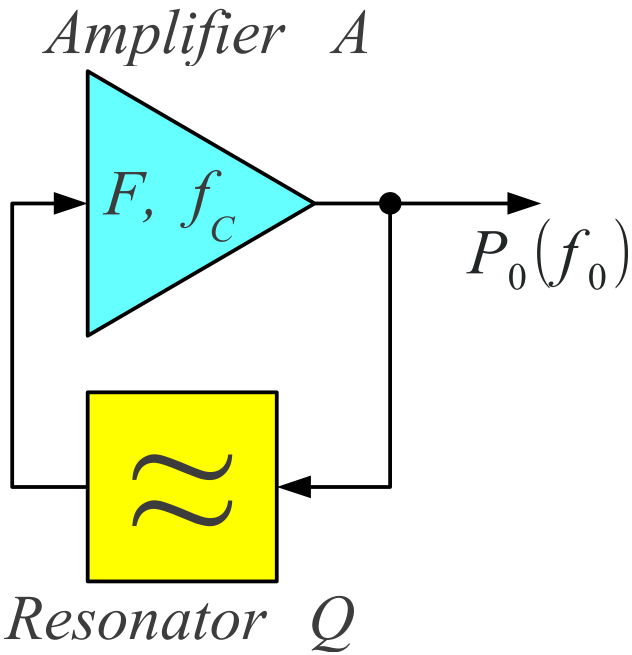
Communication Electronics

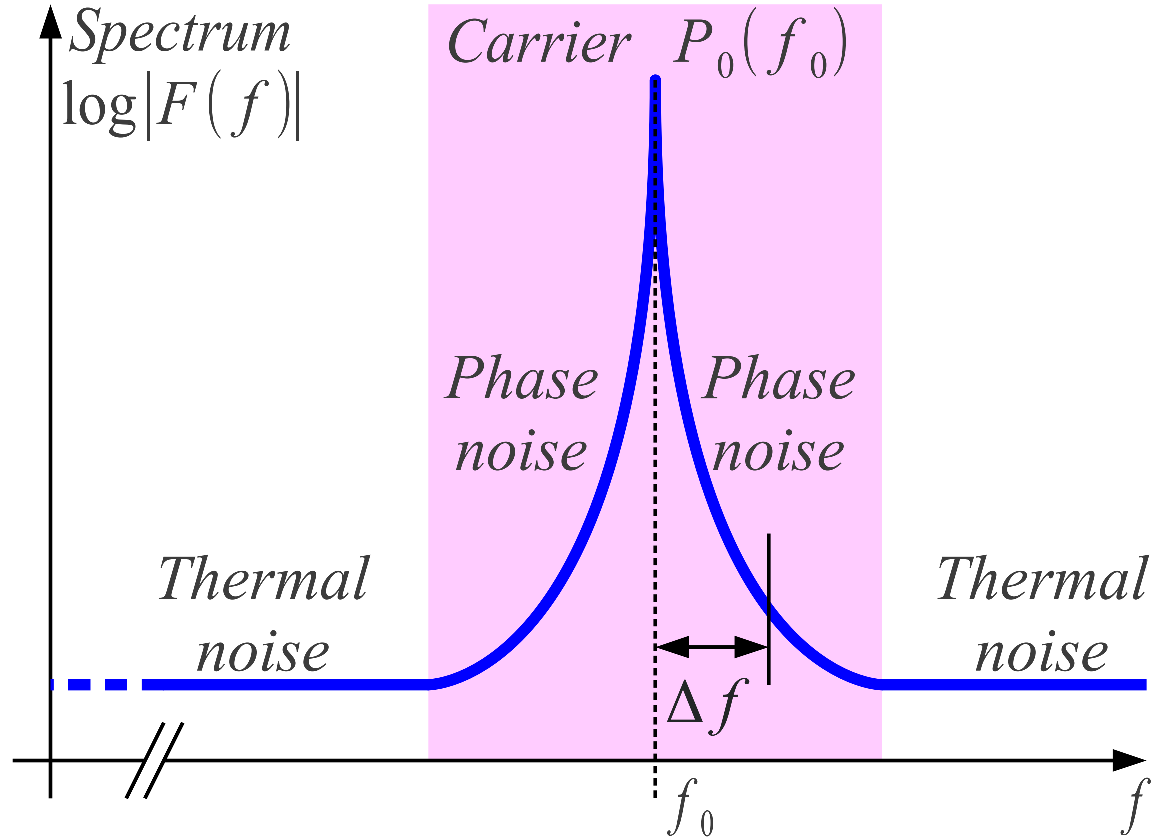
Lecture 9:

Piezoelectric devices



Communication − electronics roles of silicon





Leeson's equation:
phase−noise spectral density

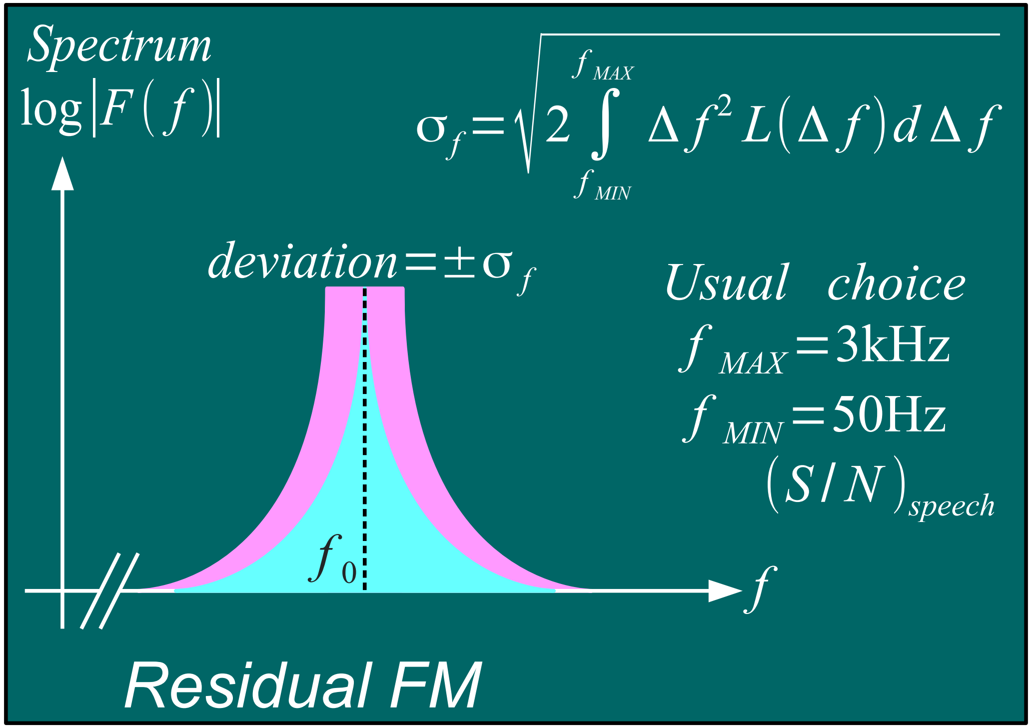
$$L(\Delta f) = \frac{1}{P_0} \cdot \frac{dP_N}{df} = \frac{1}{2} \cdot \left[1 + \left(\frac{f_0}{2 Q_L \Delta f} \right)^2 \right] \cdot \frac{k_B T_0 F}{P_0} \cdot \left(1 + \frac{f_C}{|\Delta f|} \right)$$

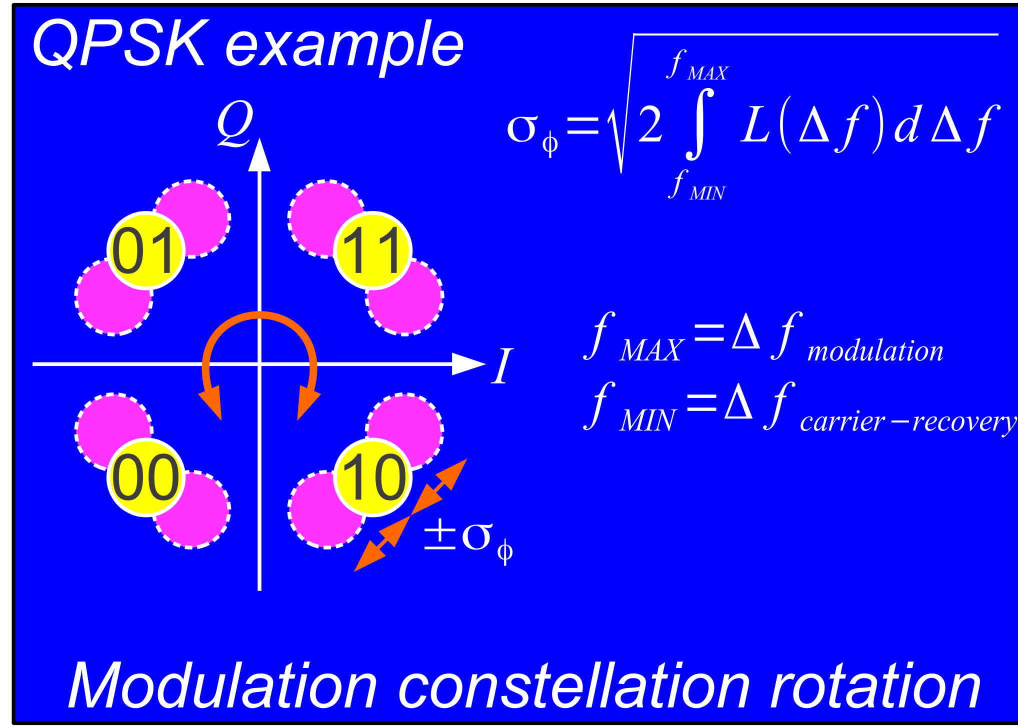
$k_B \approx 1.38 \cdot 10^{-23}\,\mathrm{J/K} \equiv$ *Boltzmann constant*
$T_0 \approx 290\mathrm{K} \equiv$ *circuit temperature*
$F \equiv$ *amplifier noise figure*
$f_C \equiv$ *flicker noise corner frequency*

$Q_L \equiv$ *loaded resonator Q*
$Q_L \approx 30$ (*LC resonant circuit*)
$Q_L \approx 1000$ (*electrical cavity*)
$Q_L \approx 30000$ (*quartz crystal*)

Oscillator phase noise

$$L(\Delta f)_{\mathrm{dBc/Hz}} = 10 \log_{10} \left[L(\Delta f) \cdot 1\mathrm{Hz} \right]$$





Analog radio link:

$Q_L \approx 30 \ldots 1000$

SSB (A3j w/o carrier) $\rightarrow f_0 < 30\text{MHz}$

FM (speech B=15kHz) $\rightarrow f_0 < 1\text{GHz}$

FM (picture B=30MHz) $\rightarrow f_0 < 30\text{GHz}$

Digital radio link:

$Q_L \approx 1000 \ldots 30000$

Dense OFDM (N>1000) $\rightarrow f_0 < 1\text{GHz}$

Coarse OFDM (N<100) $\rightarrow f_0 < 10\text{GHz}$

Single-carrier QPSK $\rightarrow f_0 < 100\text{GHz}$

Phase − noise constraints

1880 – Jacques & Pierre Curie discover the piezoelectric effect

1905 – Giorgio Spezia hydrothermal growth of quartz crystals in lab

1917 – First use of the piezoelectric effect in sonar

1918 – First use of a quartz crystal in an oscillator

1926 – First broadcast transmitter with a quartz oscillator

1927 – Discovery of a thermally-compensated quartz cut

1927 – First clock with a quartz crystal

1934 – First practical thermally-compensated "AT" cut

1949 – High-Q, high-stability "AT" cut developed

1956 – First artificial synthetic quartz crystals available

1956 – Described first TCXO

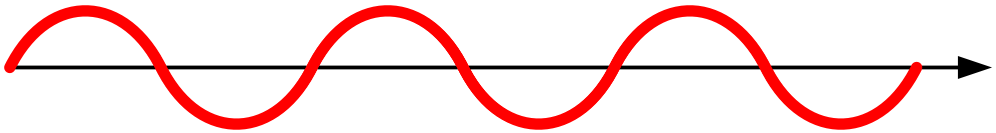
1972 – Tuning-fork quartz crystal for wrist watches

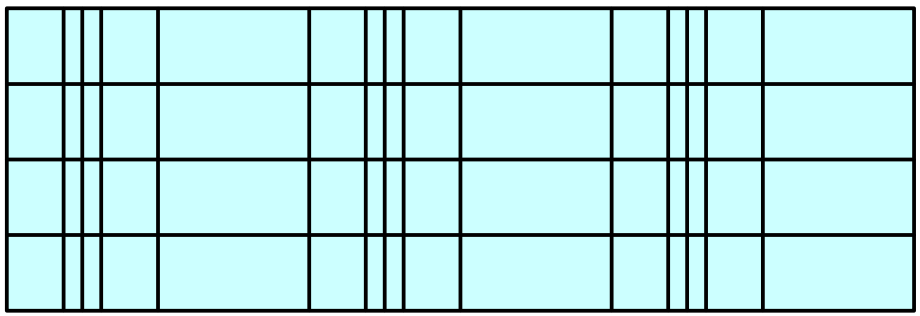
1974 – Predicted "SC" cut and verified 1976

History of quartz in electronics

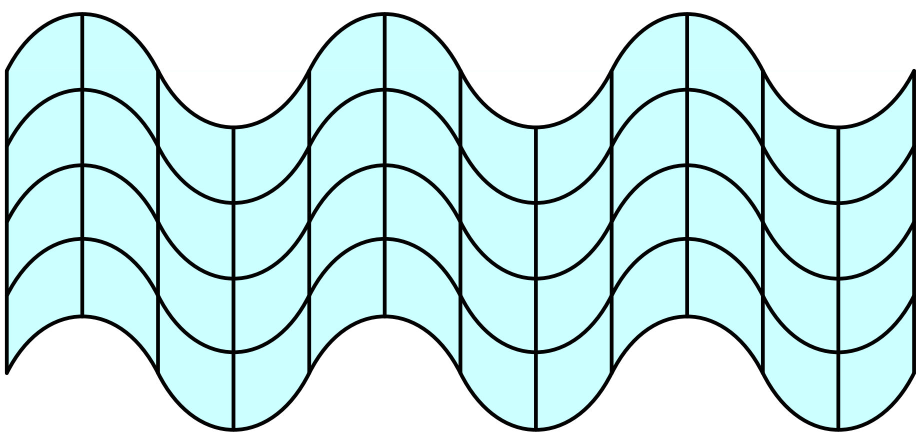
Mechanical waves

$v \approx 2\text{km/s} \ldots 12\text{km/s} \quad (solids)$

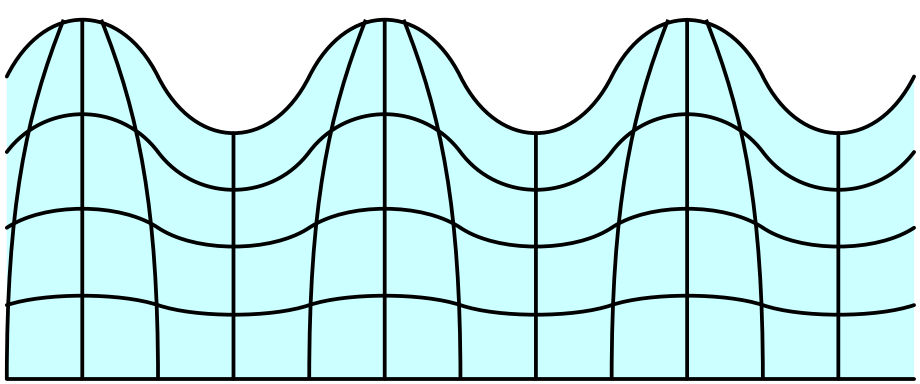




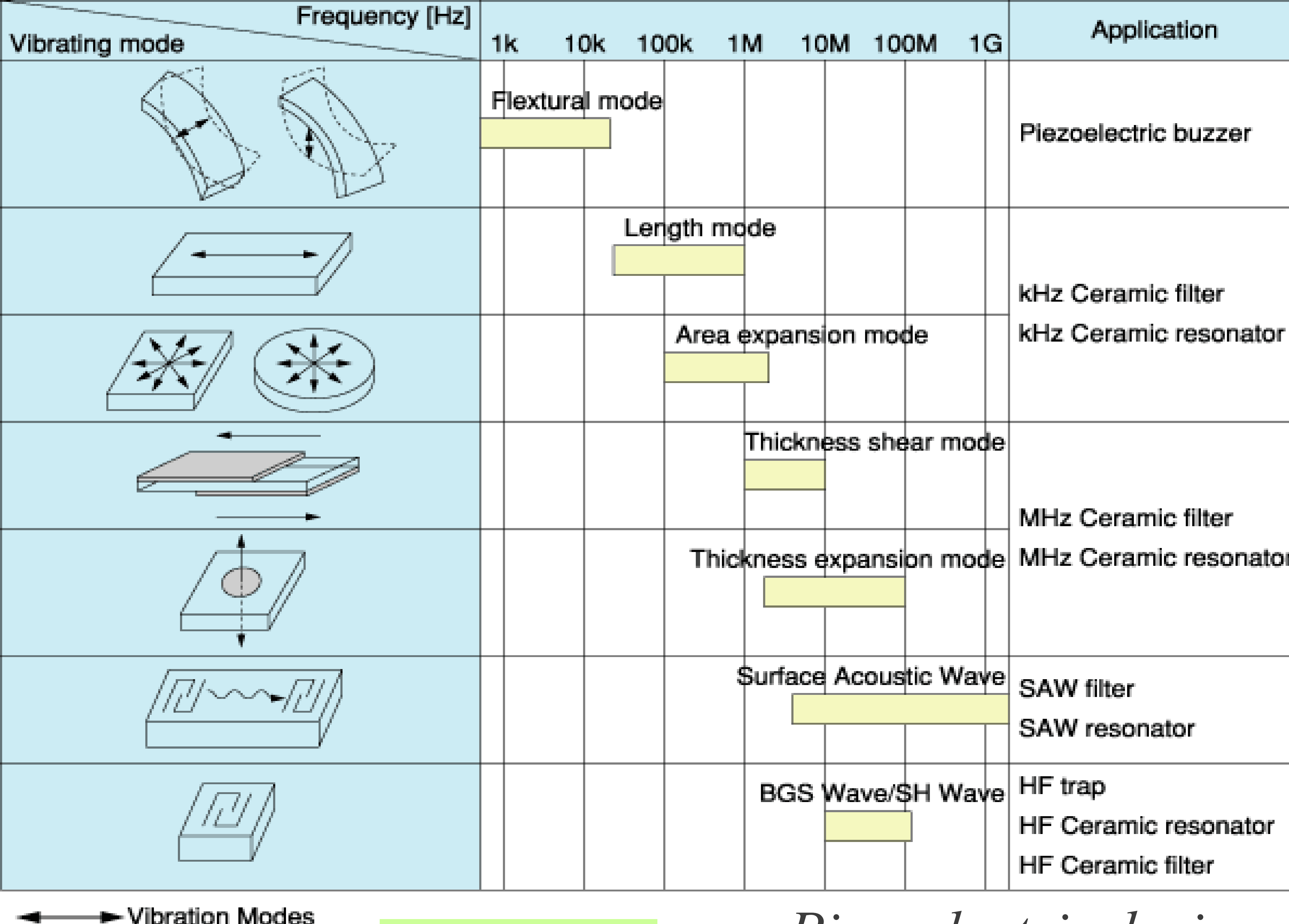
Pressure wave "P" (primary wave)
gases, liquids, solids
("BAW" bulk acoustic wave)



Shear wave "S" (secondary wave)
solids only
("BAW" bulk acoustic wave)



Surface acoustic wave "SAW"
surface of solids



$v \approx 3\mathrm{km/s} \ldots 12\mathrm{km/s}$

Piezoelectric devices

Melting point
1670°C

T<573°C
α-quartz
righthanded
& lefthanded

T>573°C
β-quartz

Mechanical
$Q>10^6$

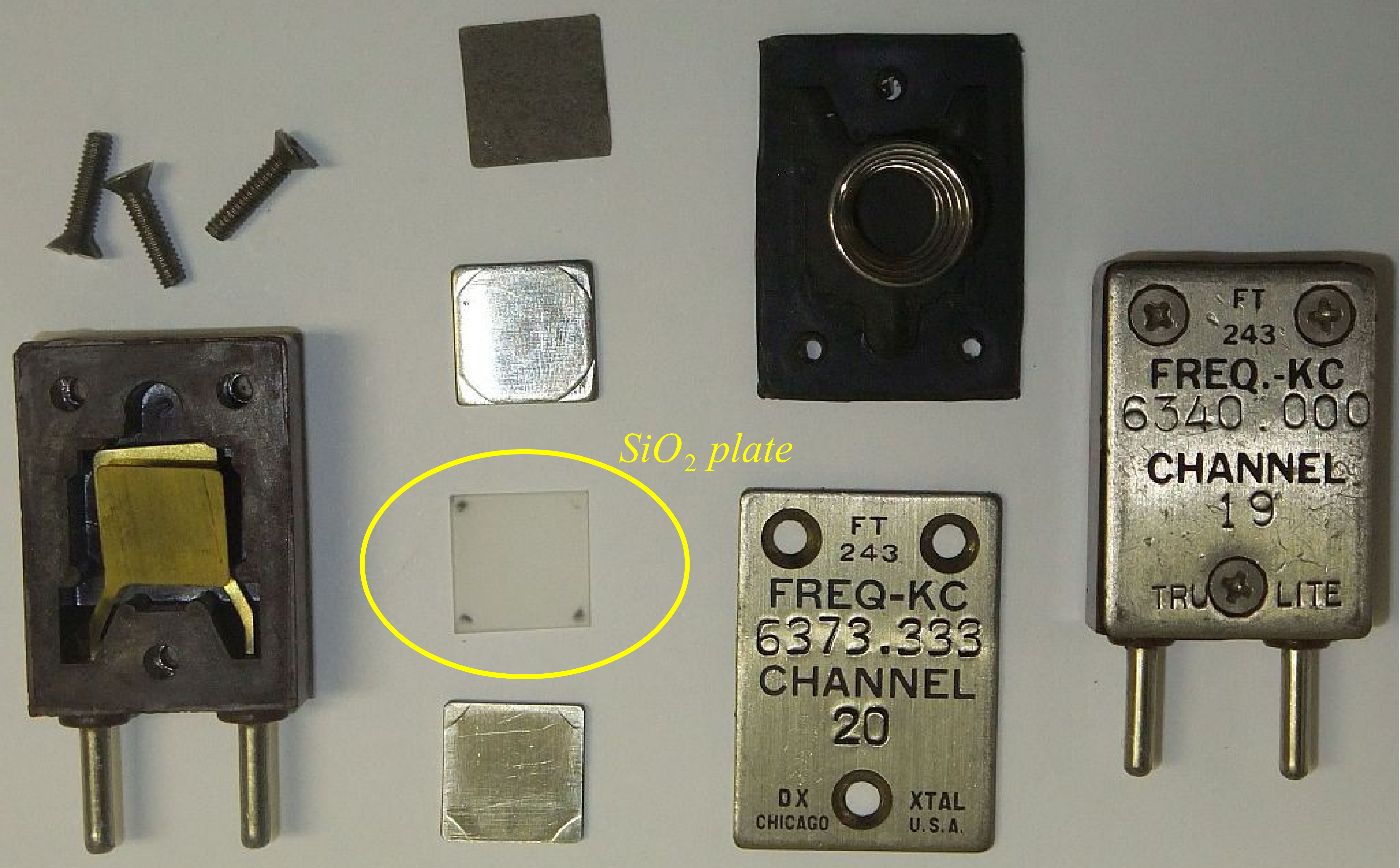
Piezoelectric

Hyderothermal growth in H_2O+NaCl (~1000 years) p≈1000bar

Both α forms present: righthanded & lefthanded (twinning)?

Impurities? Inclusions? Availability?

Natural quartz crystal



Historical quartz resonator FT243

Hydrothermal growth

$v_{growth}(z) \approx 3 \cdot v_{growth}(x)$

righthanded α-quartz

$H_2O+Na_2CO_3$

$p \approx 700...1000bar$

$T \approx 345°C \quad \Delta T \approx 10°C$

$v_{growth}(z) \approx 0.4mm/day$

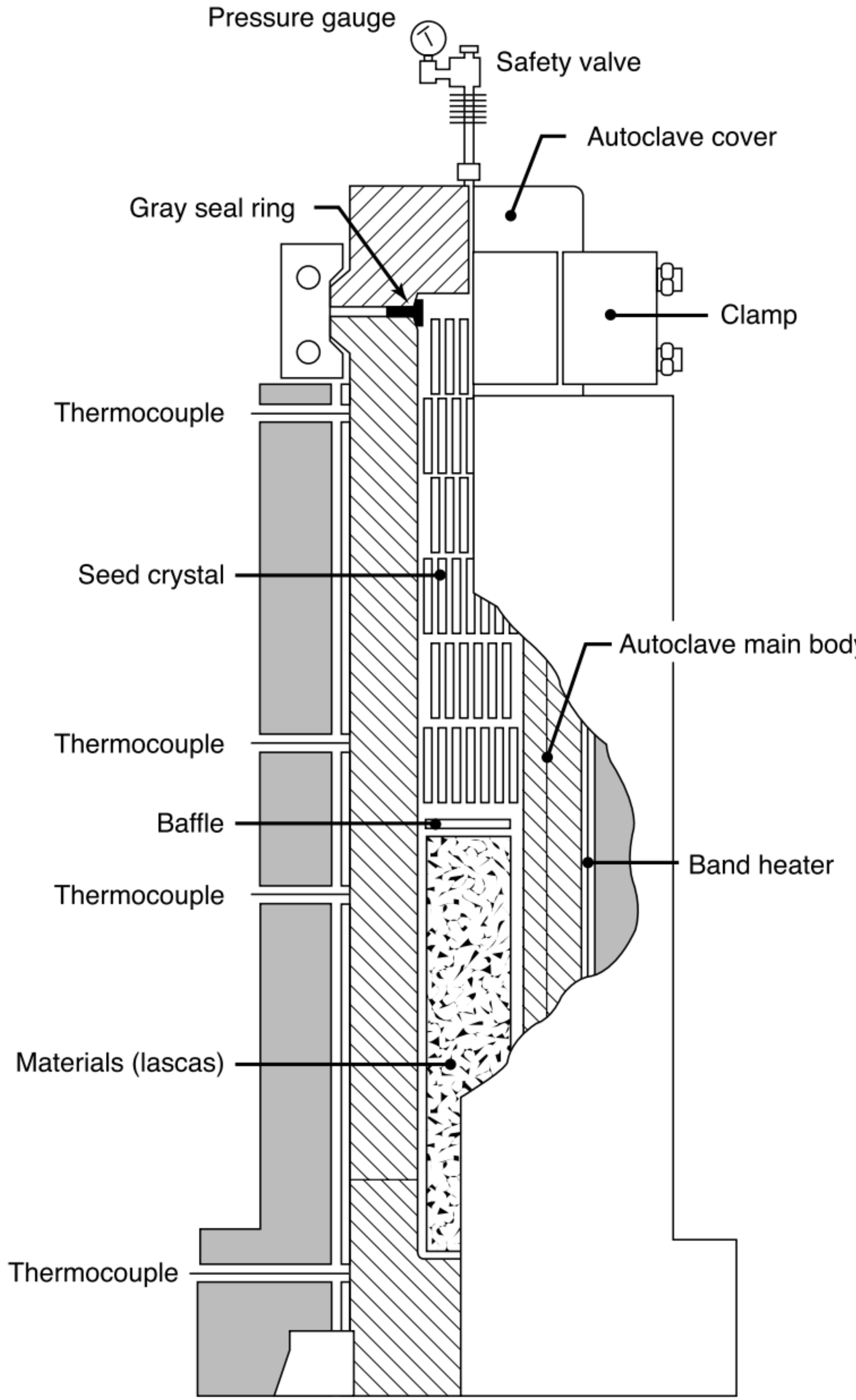
$H_2O+NaOH$

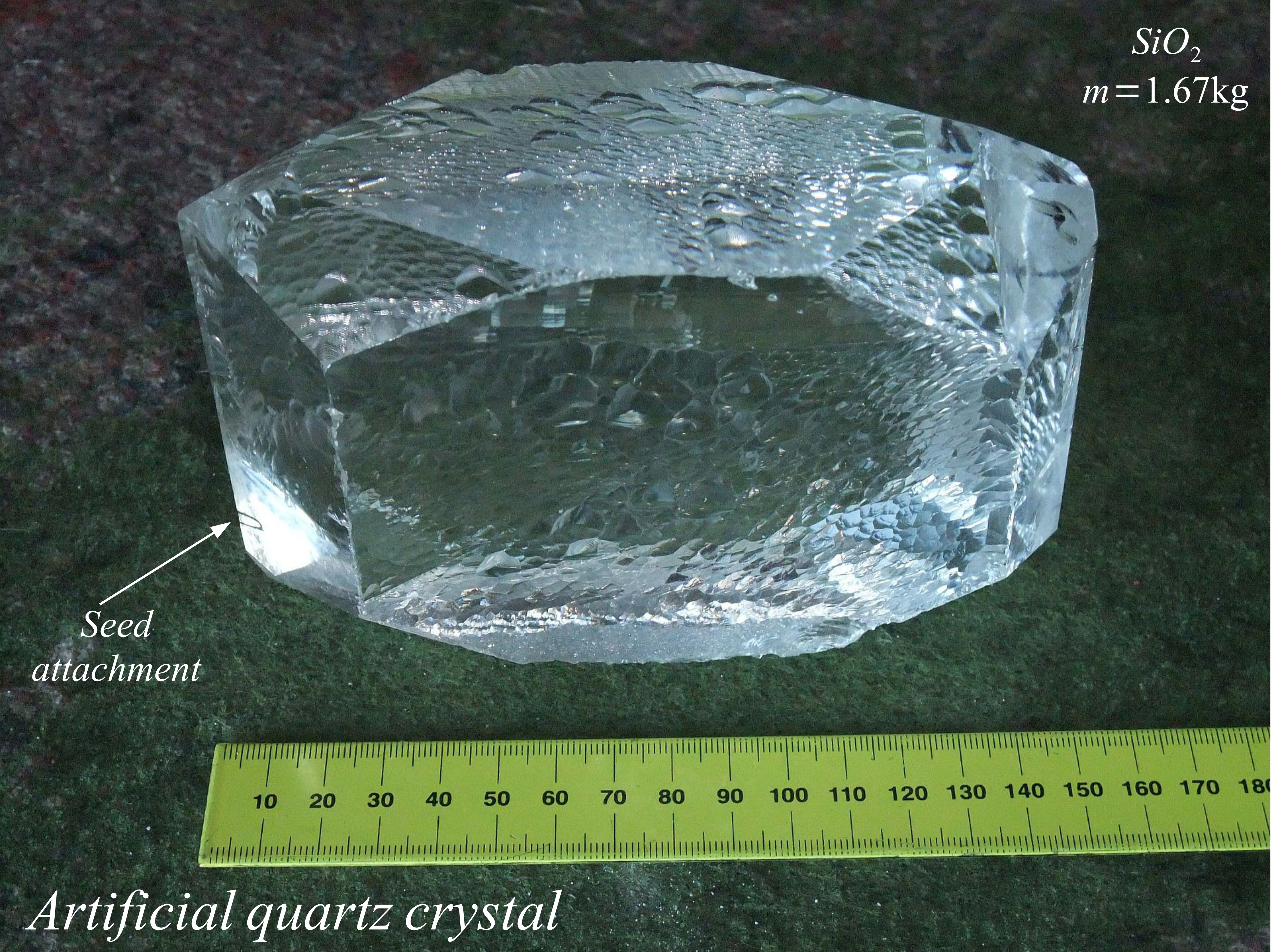
$p \approx 1000...1500bar$

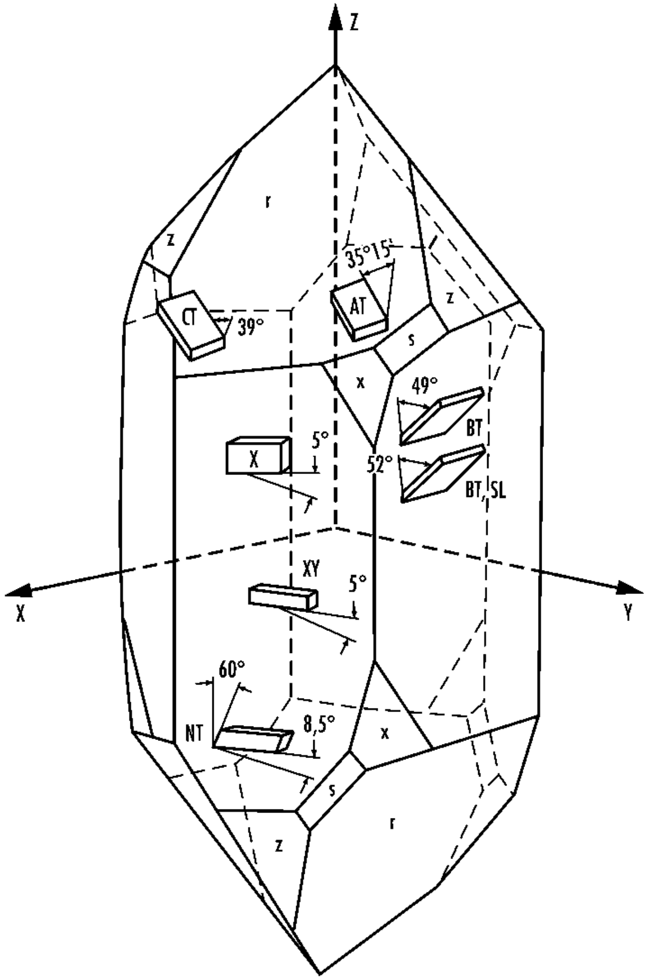
$T \approx 380°C \quad \Delta T \approx 25°C$

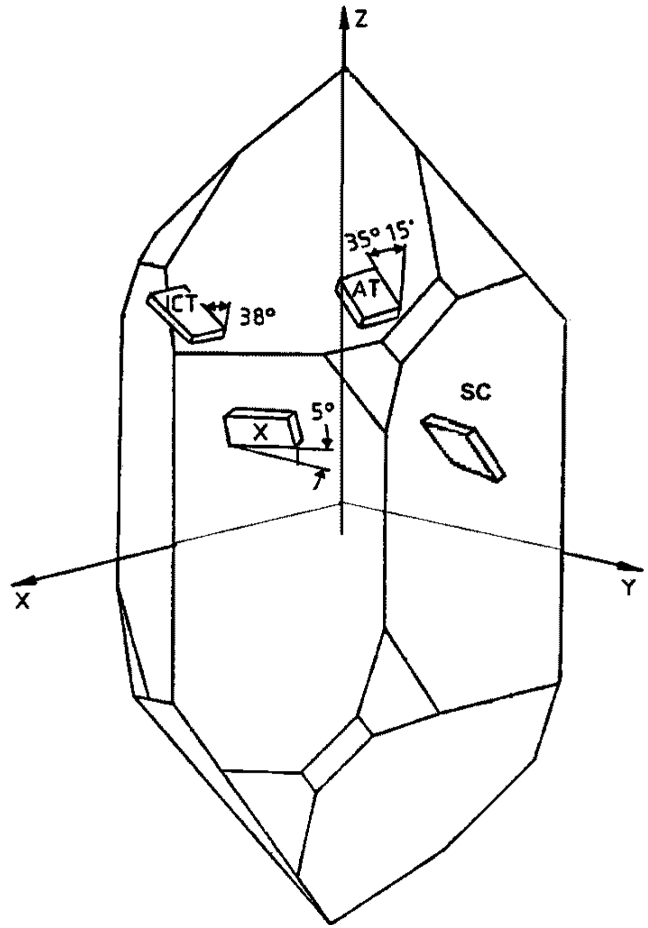
$v_{growth}(z) \approx 1mm/day$

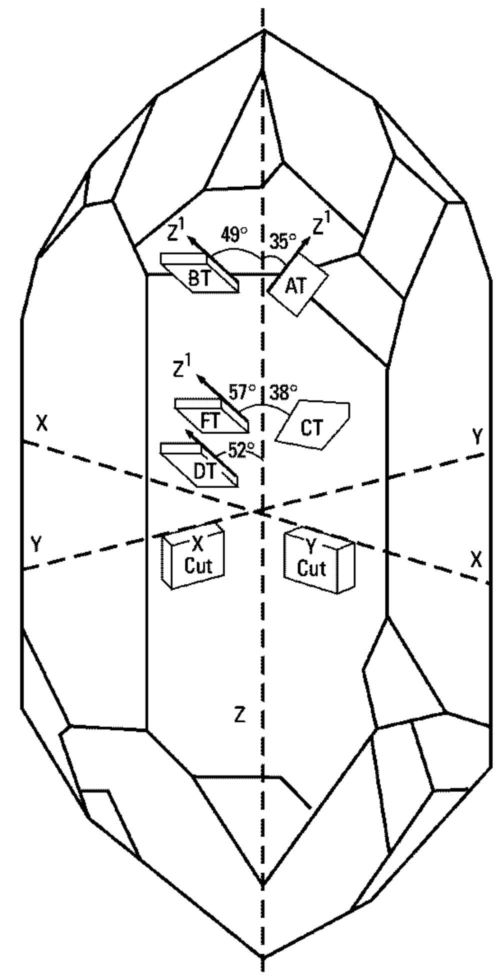
Hydrothermal growth oven

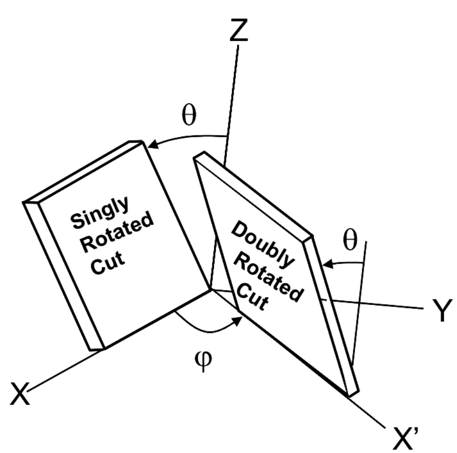


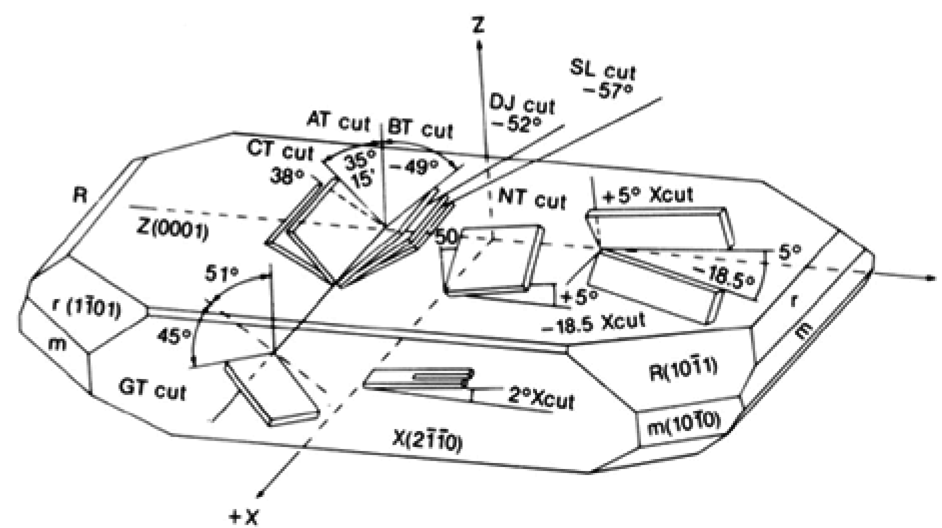

SiO_2
$m = 1.67$kg
Seed attachment
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
Artificial quartz crystal



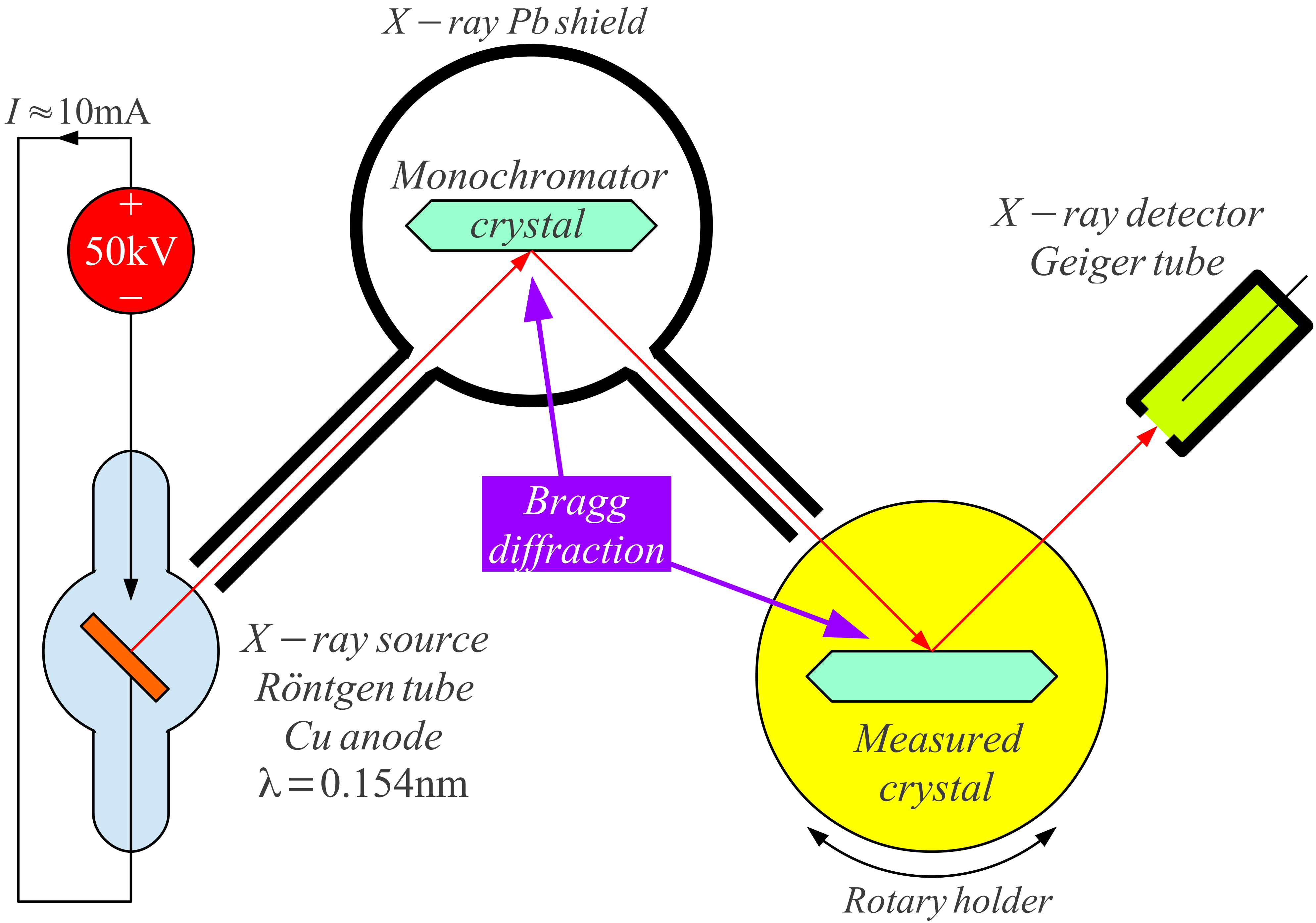




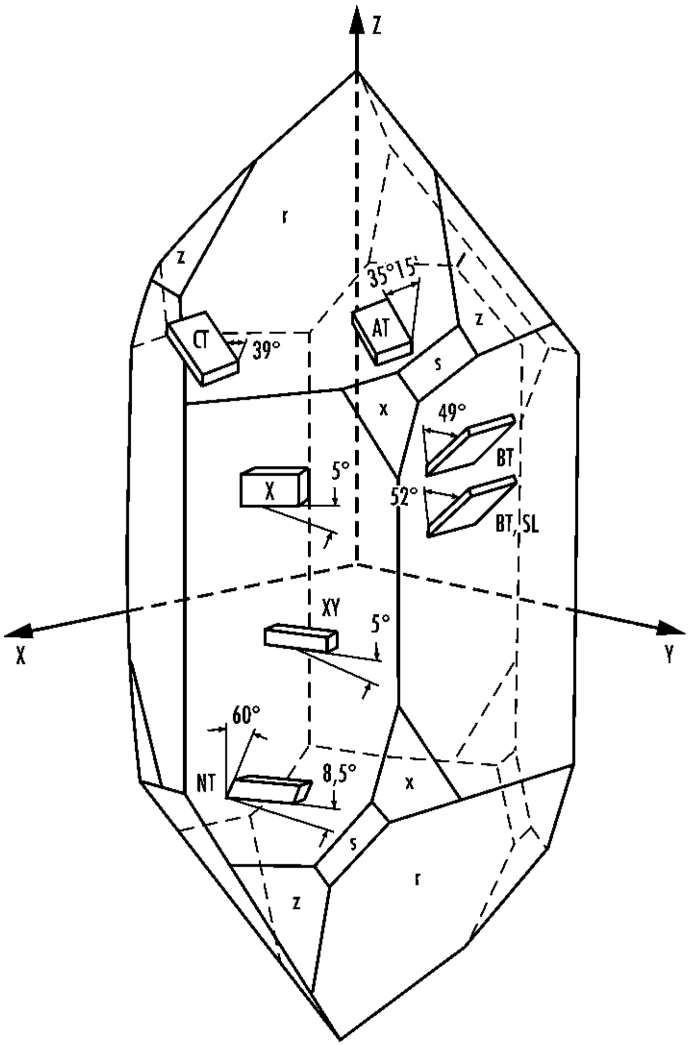


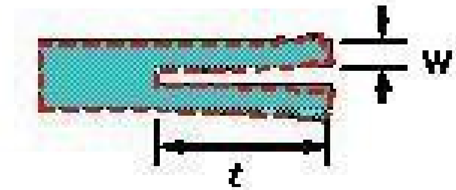
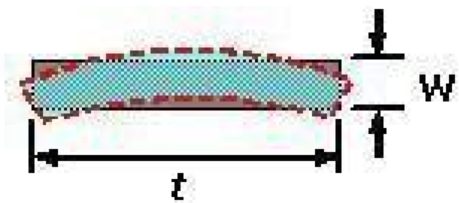
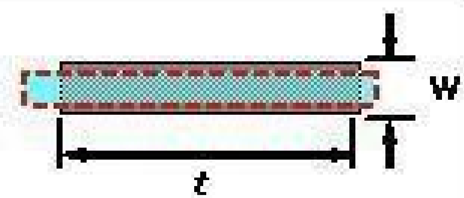
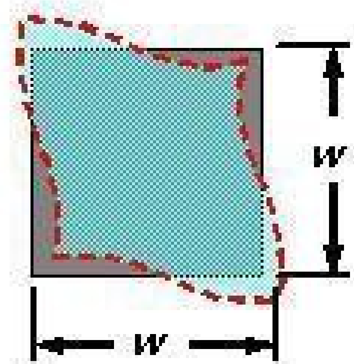
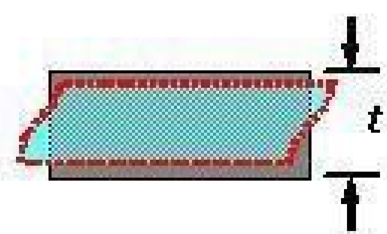


Quartz – crystal cuts



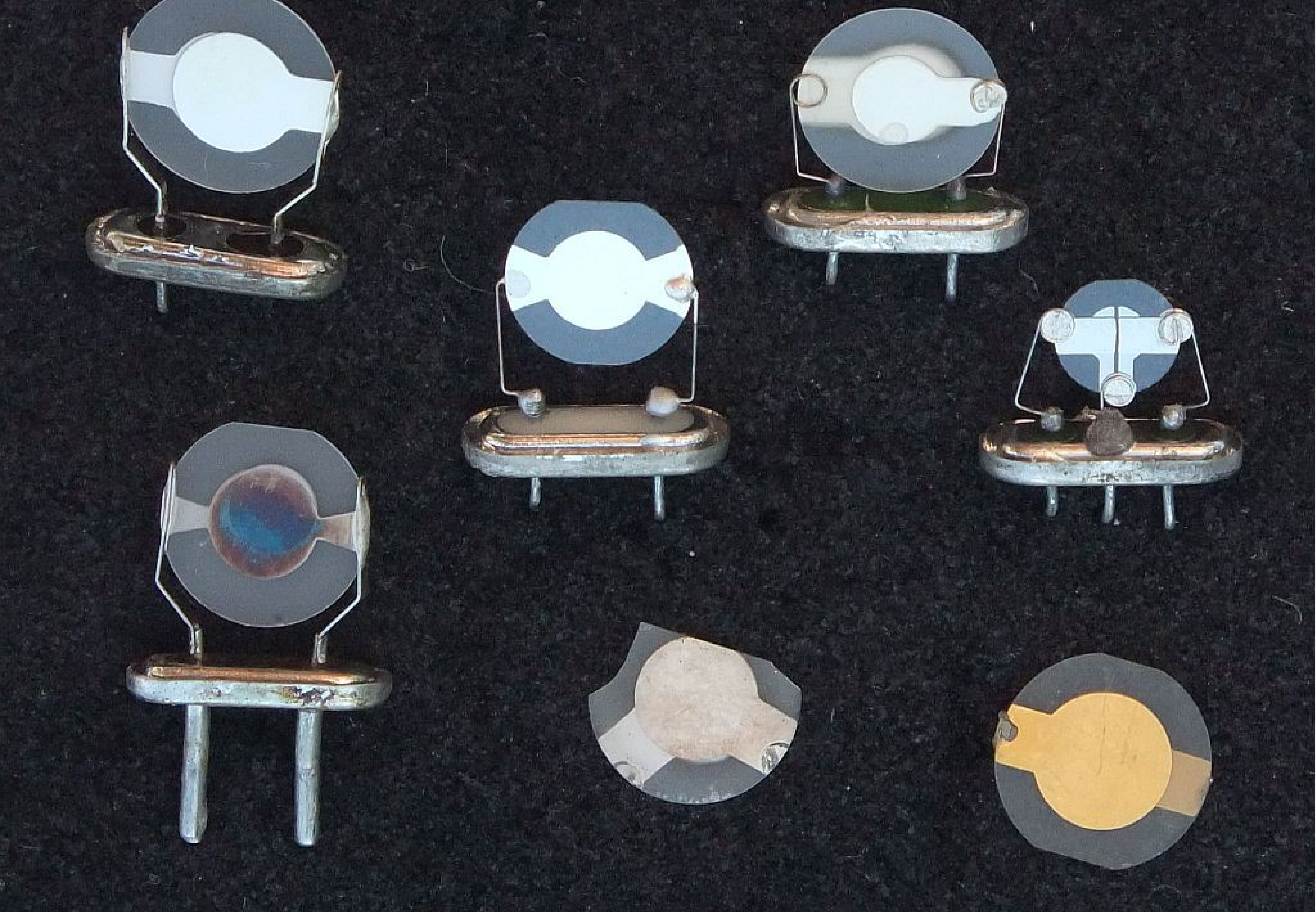
Finding the crystal axes with X rays

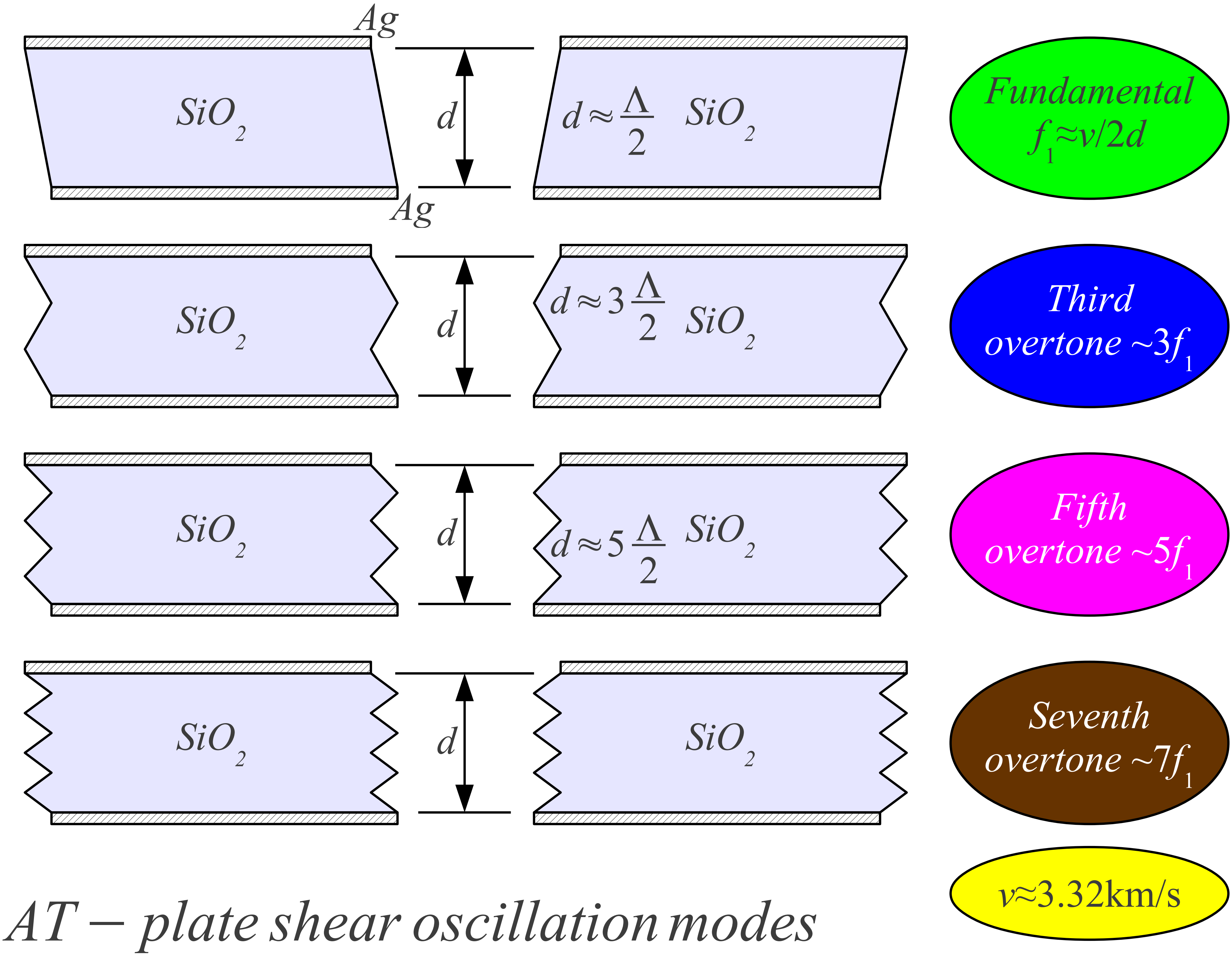


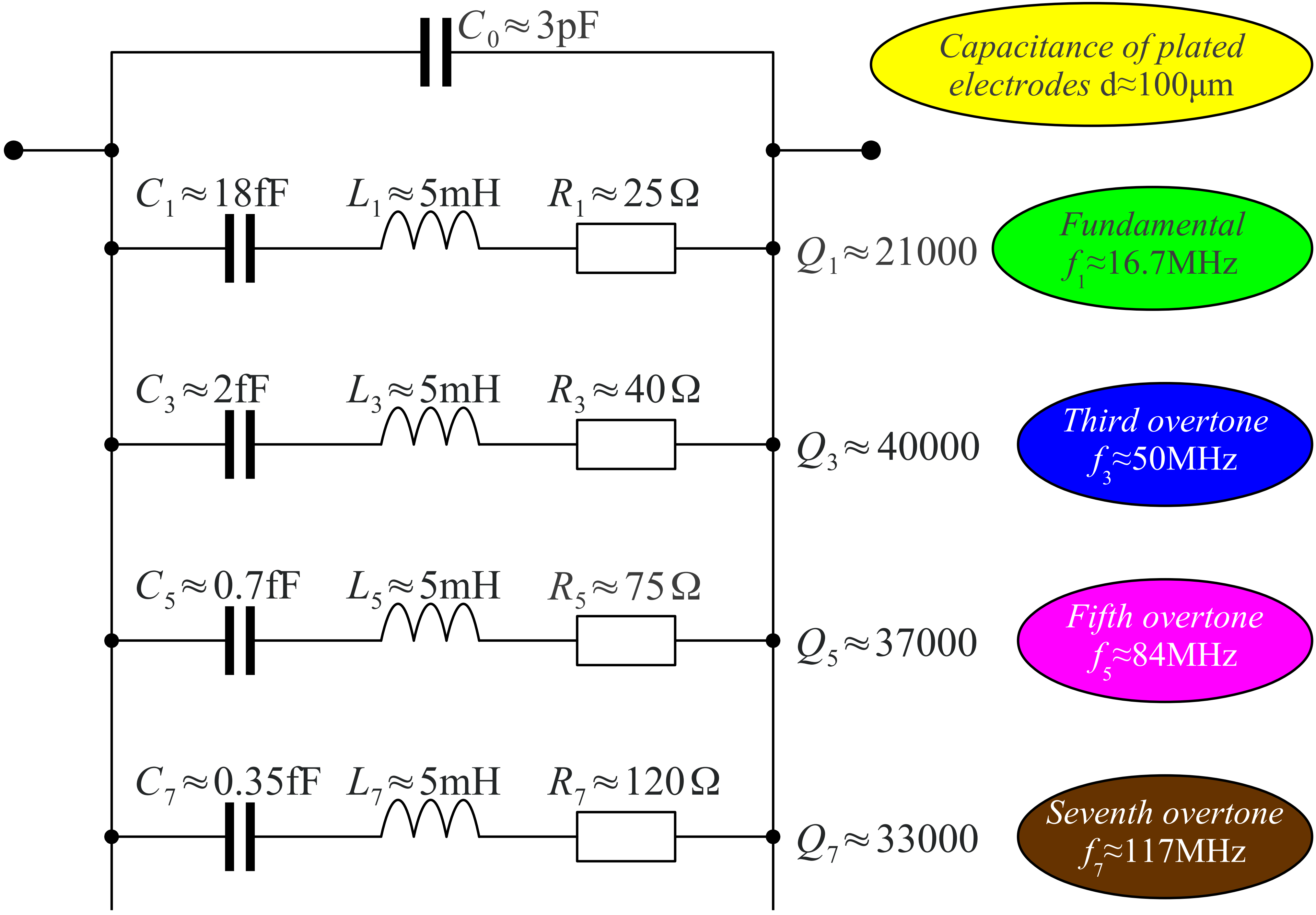
Vibration Mode		Orienation Angle
Tuning Fork		+ 2 ° X
Flexure		XY NT
Extension		+ 5 ° X - 18.5 ° X
Face Shear		DT CT SL
Thickness Shear		AT Fundamental AT 3rd Overtone AT 5th Overtone BT Fundamental

Oscillation modes

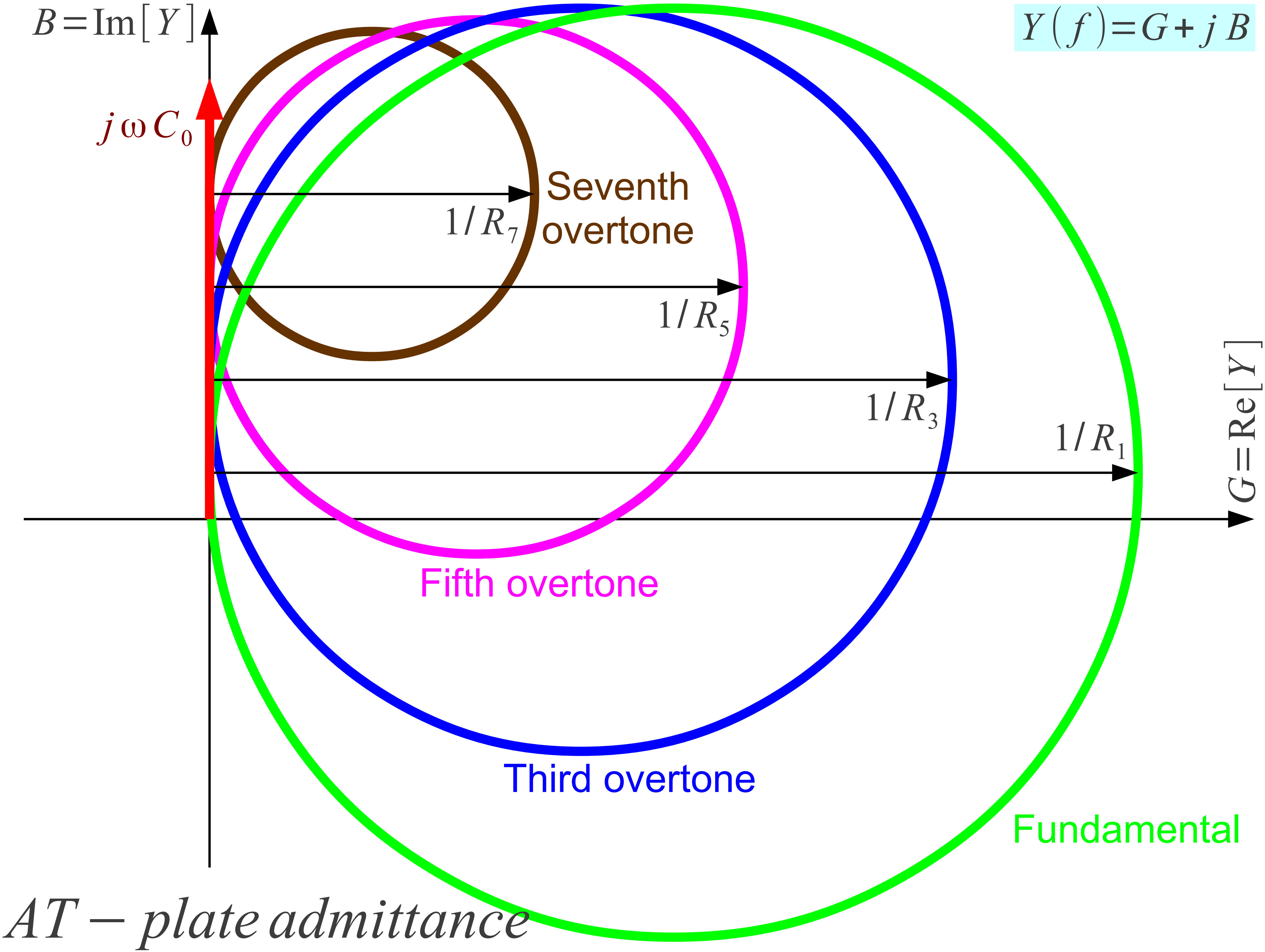
AT plates




Ag
Ag
SiO2
d
d ≈ Λ/2
Fundamental
f1≈v/2d
Third
overtone ~3f1
d ≈ 3 Λ/2
Fifth
overtone ~5f1
d ≈ 5 Λ/2
Seventh
overtone ~7f1
v≈3.32km/s
AT – plate shear oscillation modes

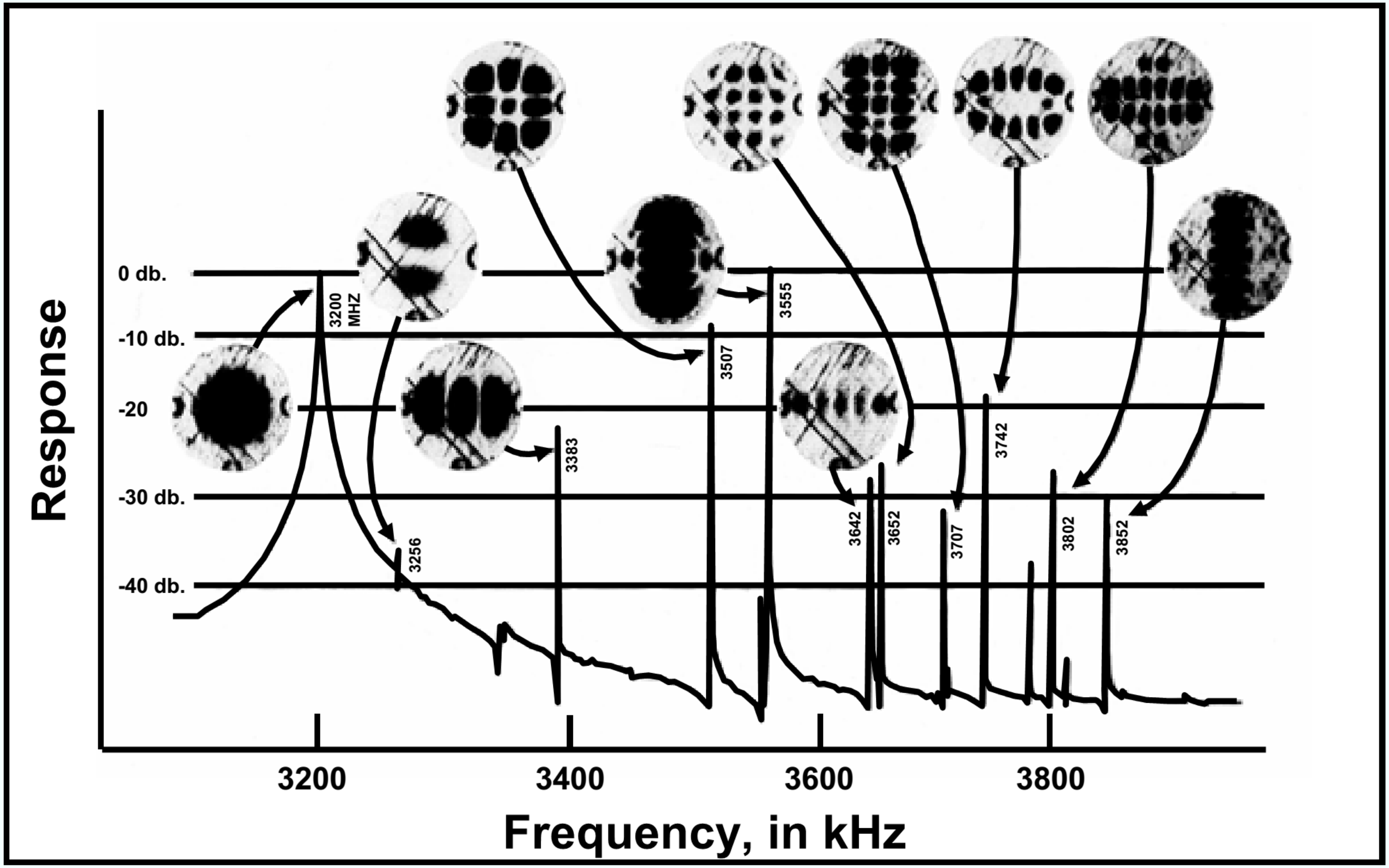


AT − plate equivalent electric circuit



B = Im[Y]
Y (f) = G + j B
j ω C0
Seventh
overtone
1 / R7
1 / R5
1 / R3
1 / R1
G = Re[Y]
Fifth overtone
Third overtone
Fundamental
AT − plate admittance

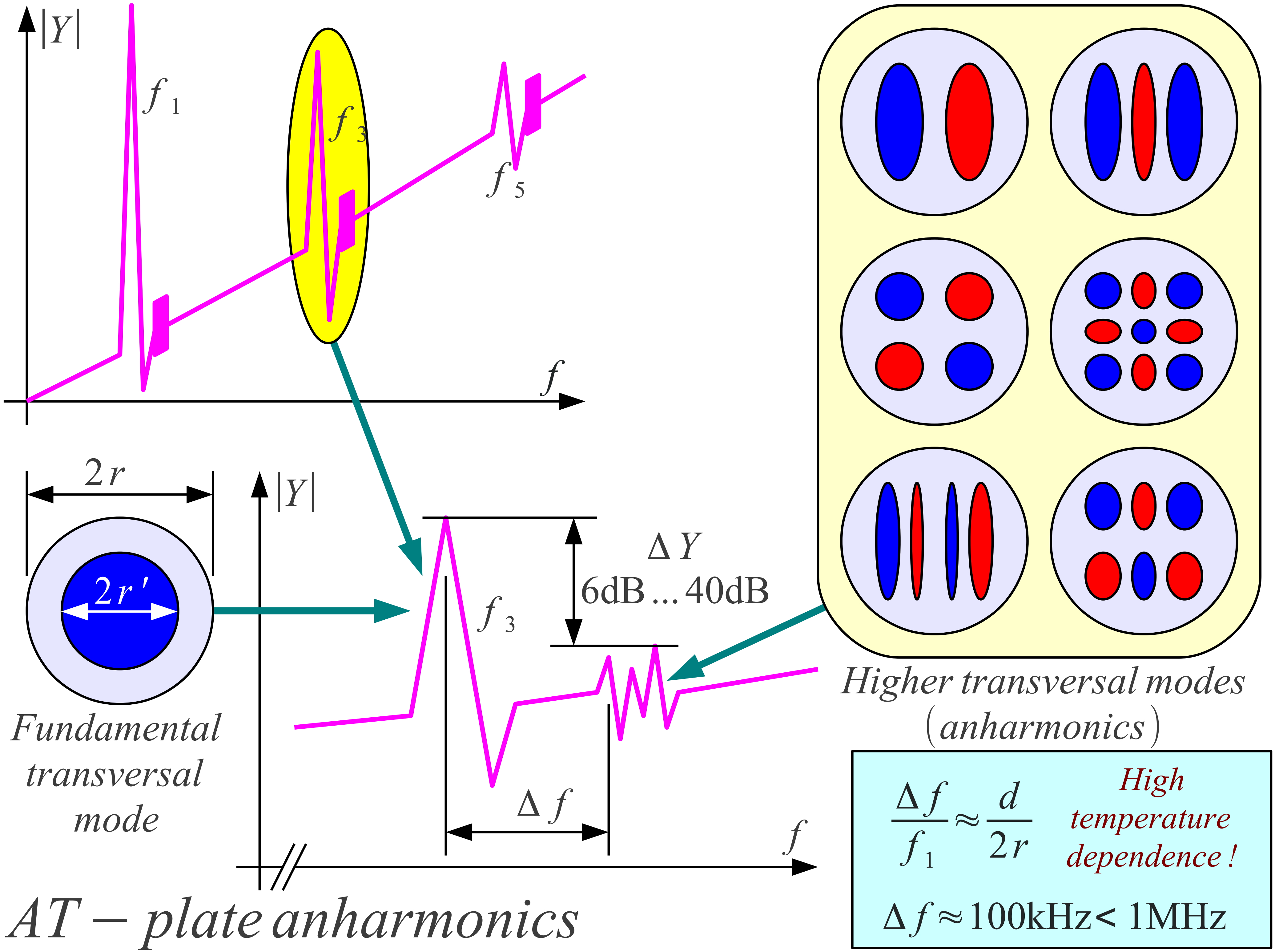
Resonant Vibrations of a Quartz Plate

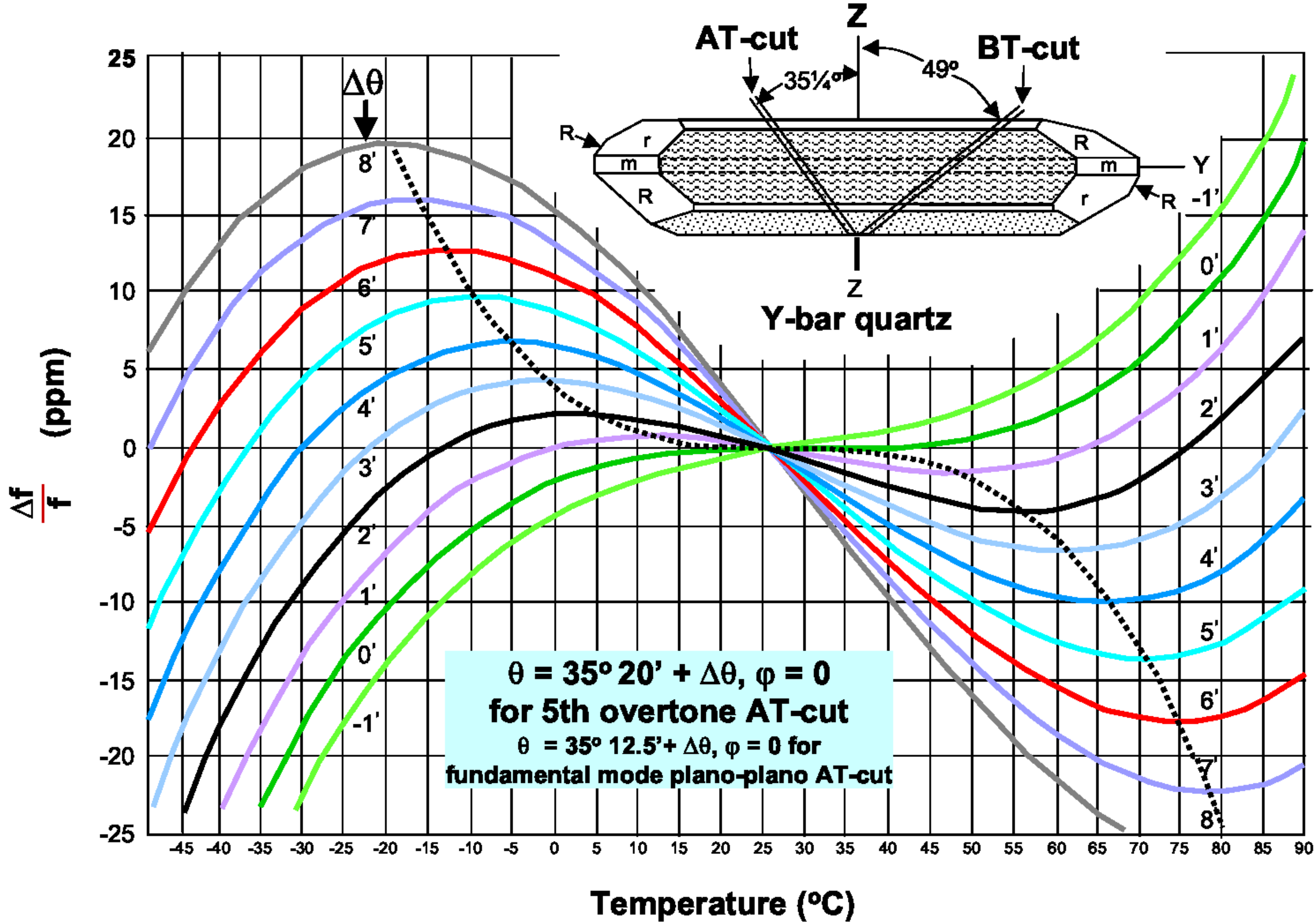


X-ray topographs ($21\cdot\bar{0}$ plane) of various modes excited during a frequency scan of a fundamental mode, circular, AT-cut resonator. The first peak, at 3.2 MHz, is the main mode; all others are unwanted modes. Dark areas correspond to high amplitudes of displacement.

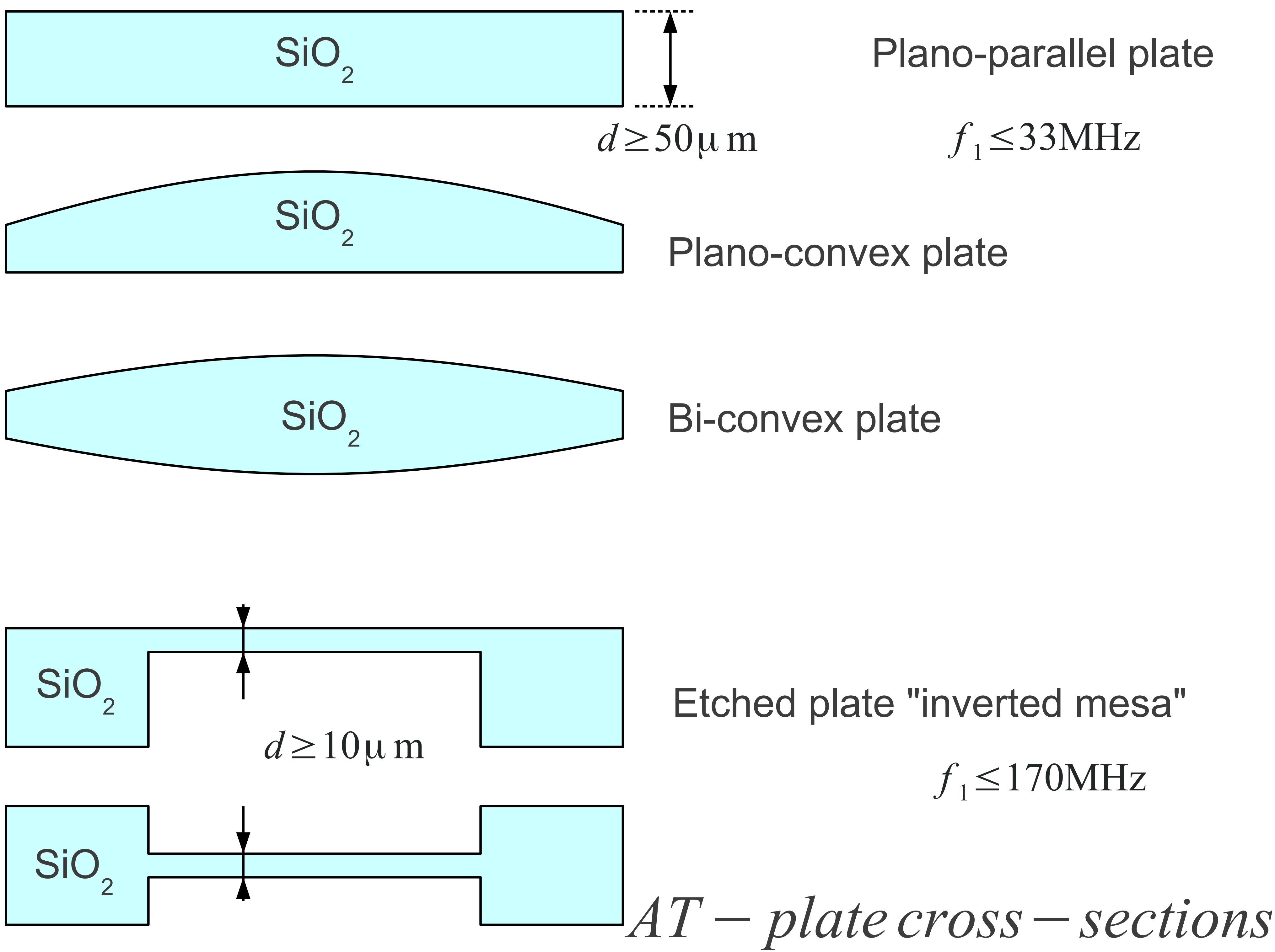
$AT - plate\ oscillation\ modes\left(anharmonics\right)$

AT – plate anharmonics

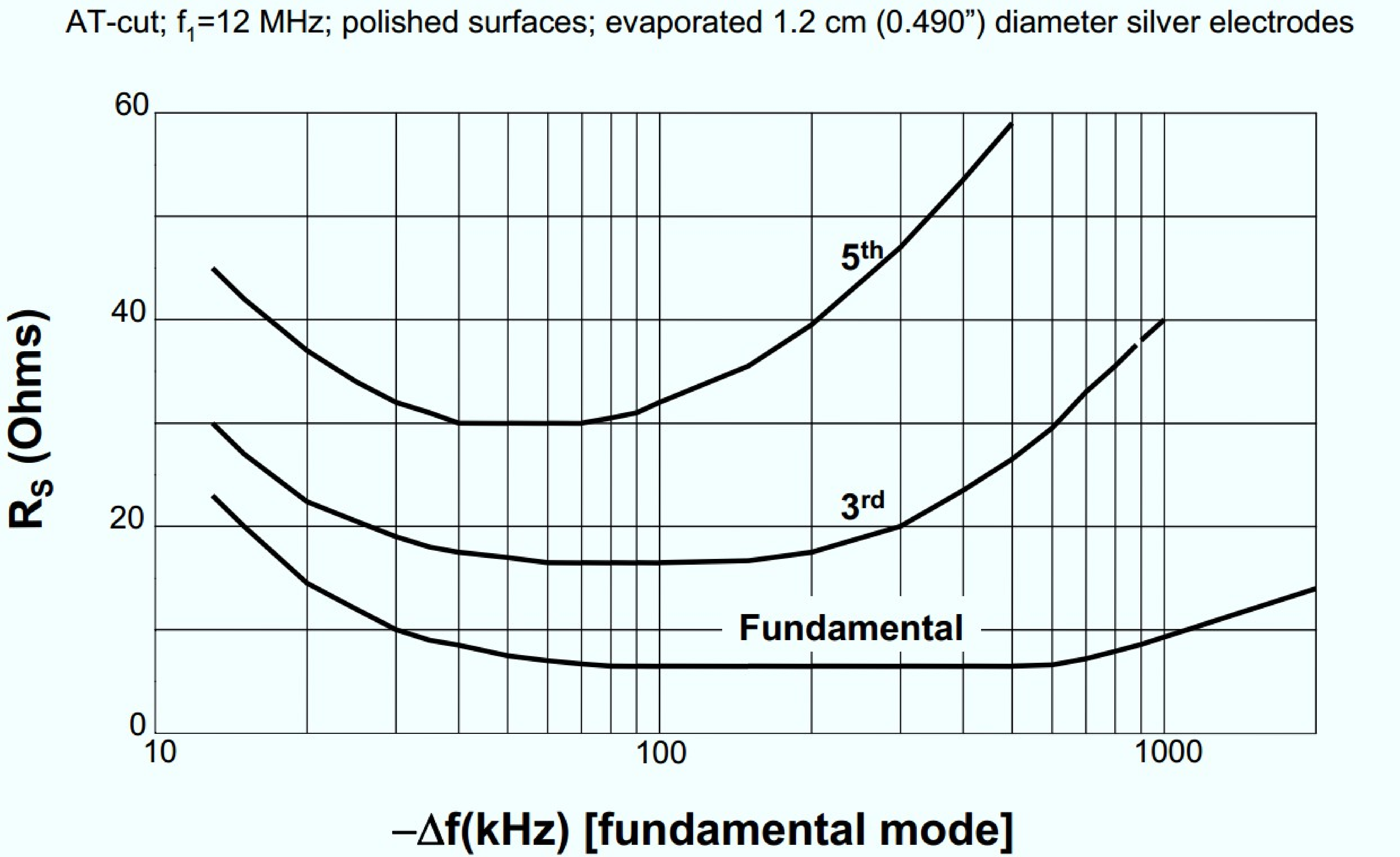




AT – plate temperature dependence

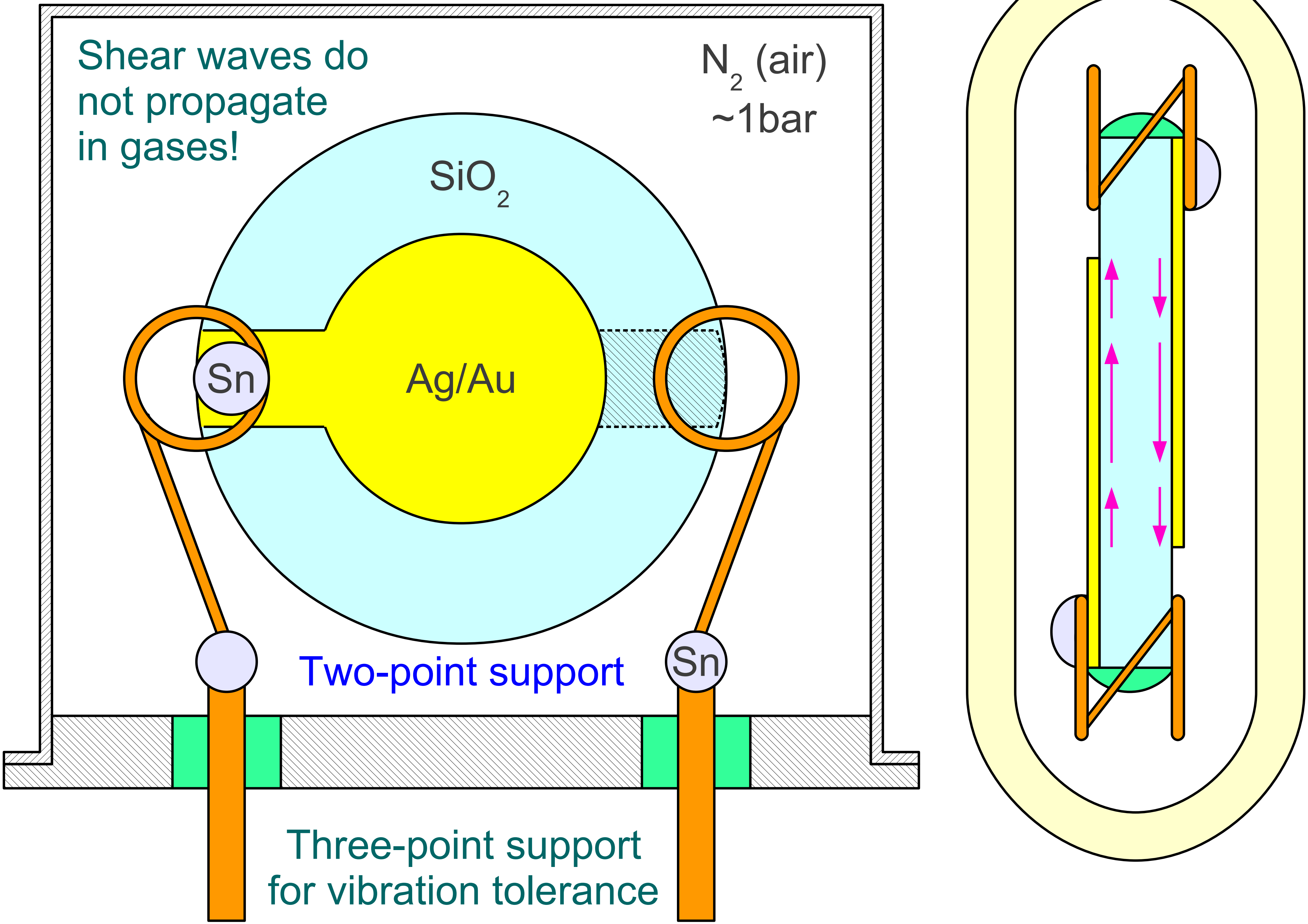

SiO2
Plano-parallel plate
d≥50μm
f1≤33MHz
SiO2
Plano-convex plate
SiO2
Bi-convex plate
SiO2
Etched plate "inverted mesa"
d≥10μm
f1≤170MHz
SiO2
AT − plate cross − sections

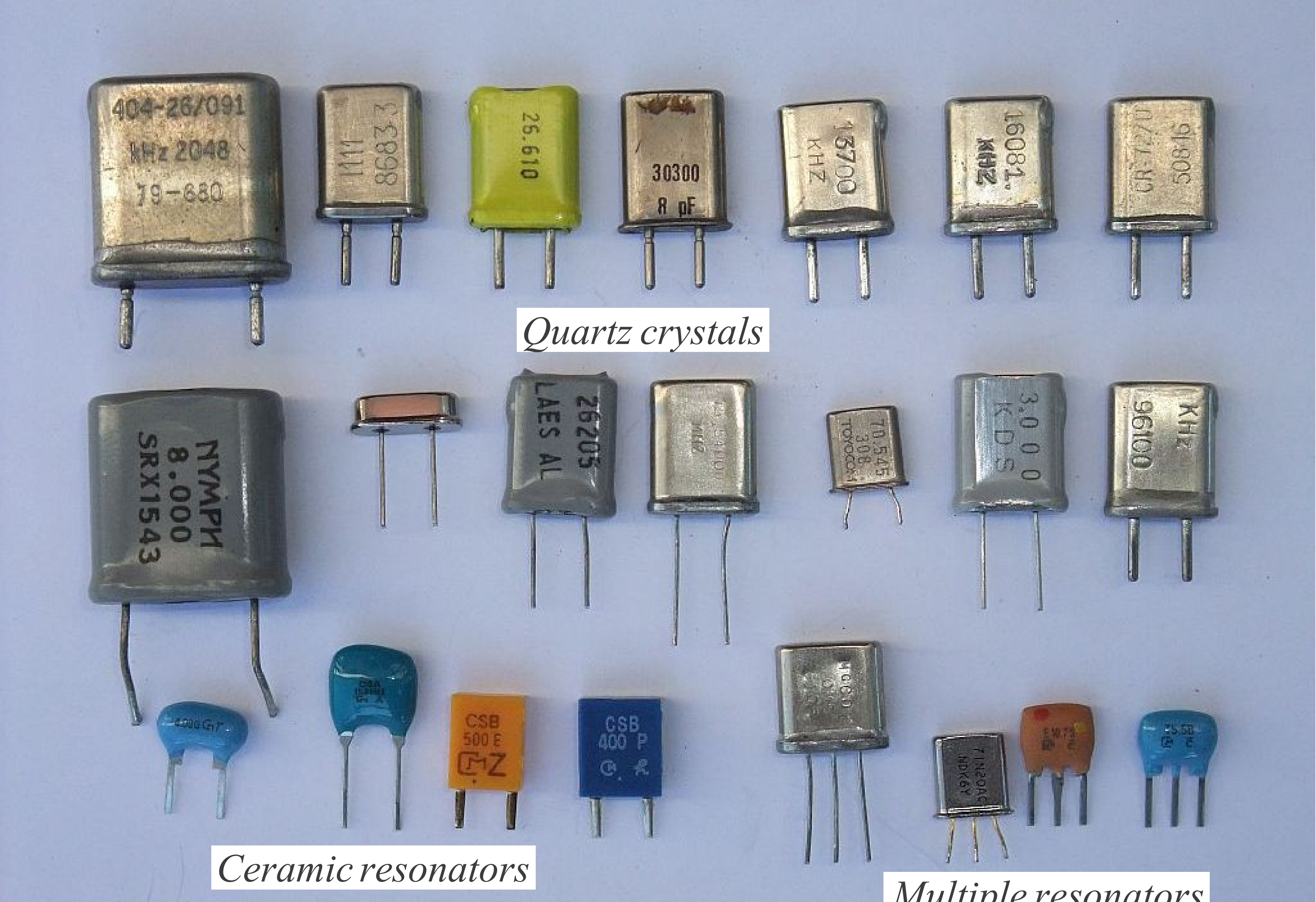
Resistance vs. Electrode Thickness



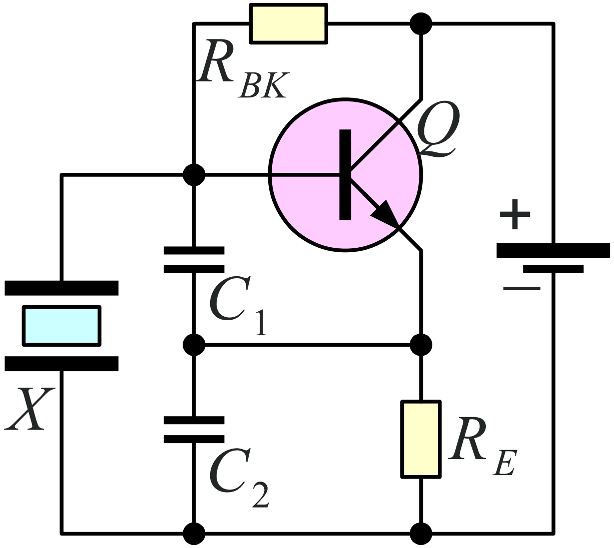
Effects of plated electrodes

AT – plate housing



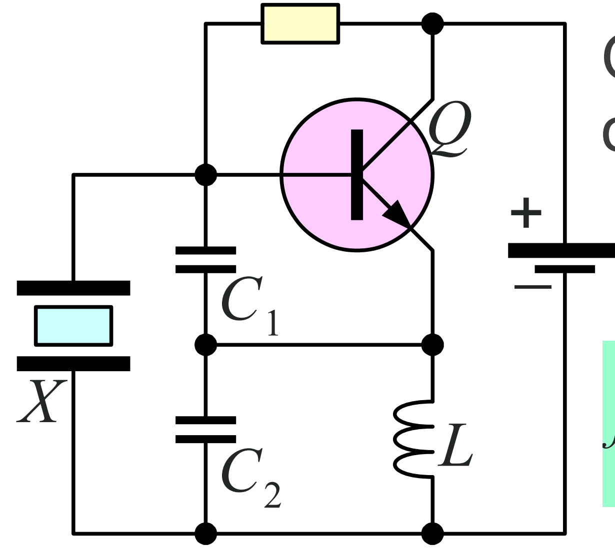


Piezoelectric – resonator housings



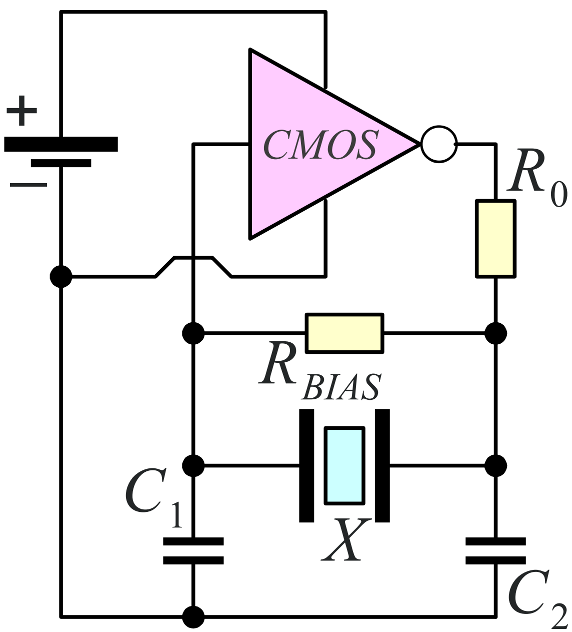
Fundamental f_1

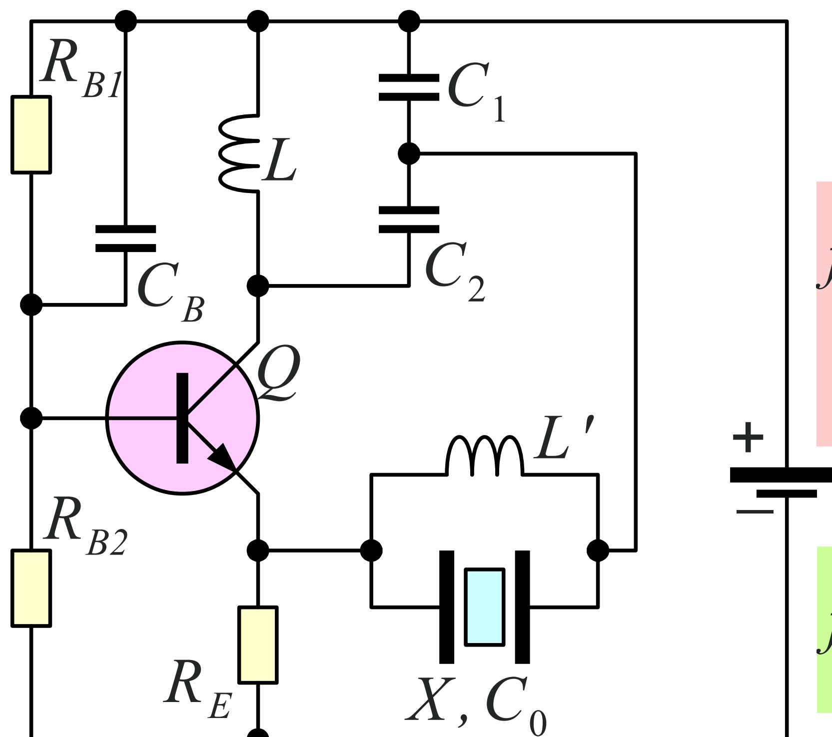
Pierce (Colpitts)



Overtone oscillator f_3

$$f_1 < \frac{1}{2\pi\sqrt{LC_2}} < f_3$$



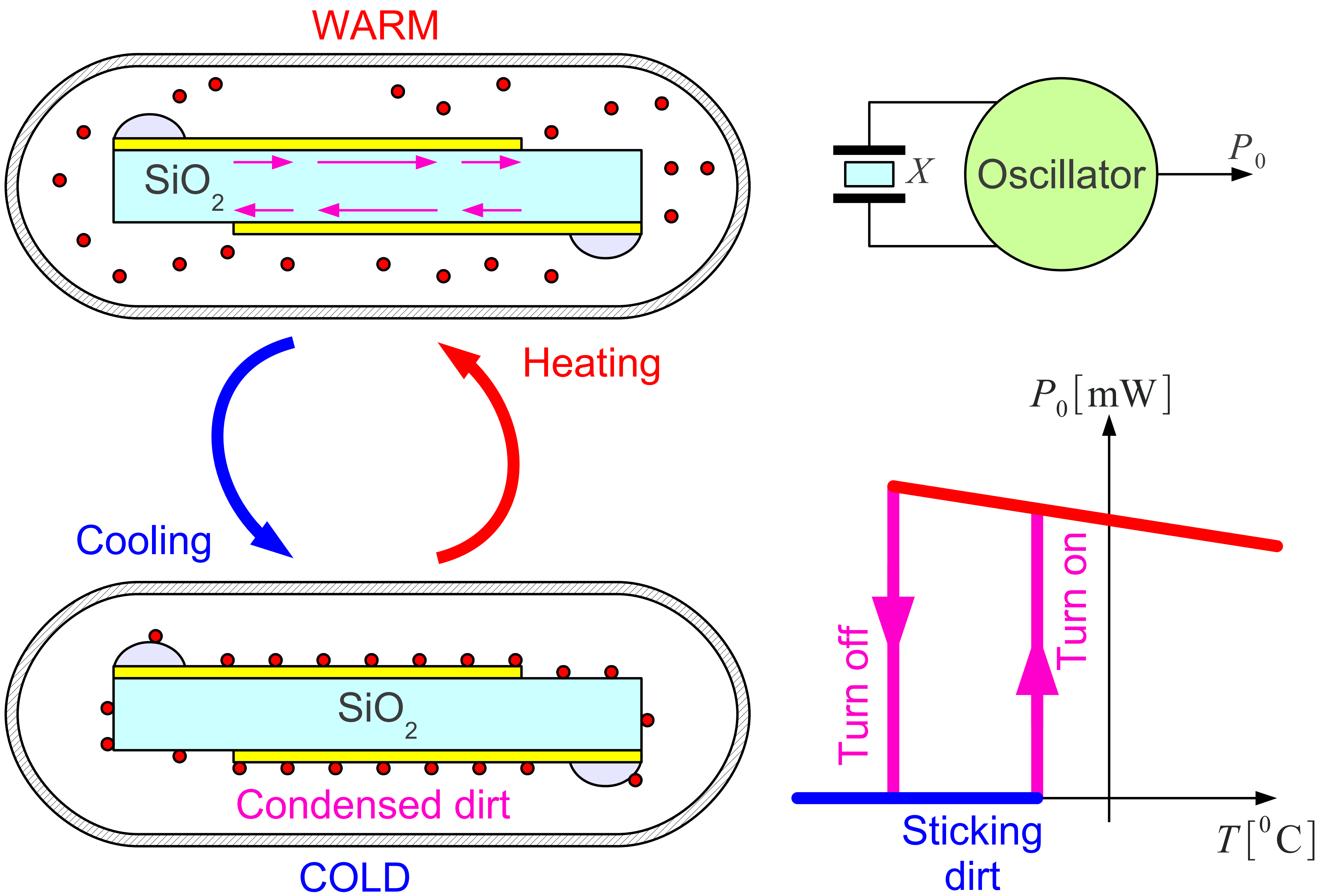


Overtone oscillator f_5

$$f_5 = \frac{1}{2\pi\sqrt{L\frac{C_1 C_2}{C_1 + C_2}}}$$

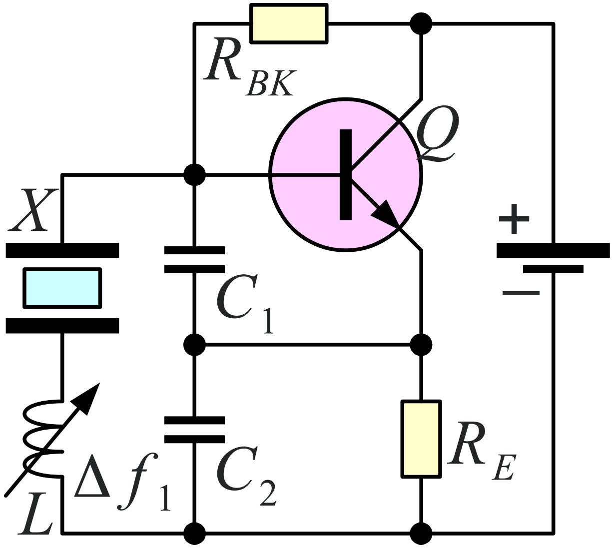
$$f_5 = \frac{1}{2\pi\sqrt{L' C_0}}$$

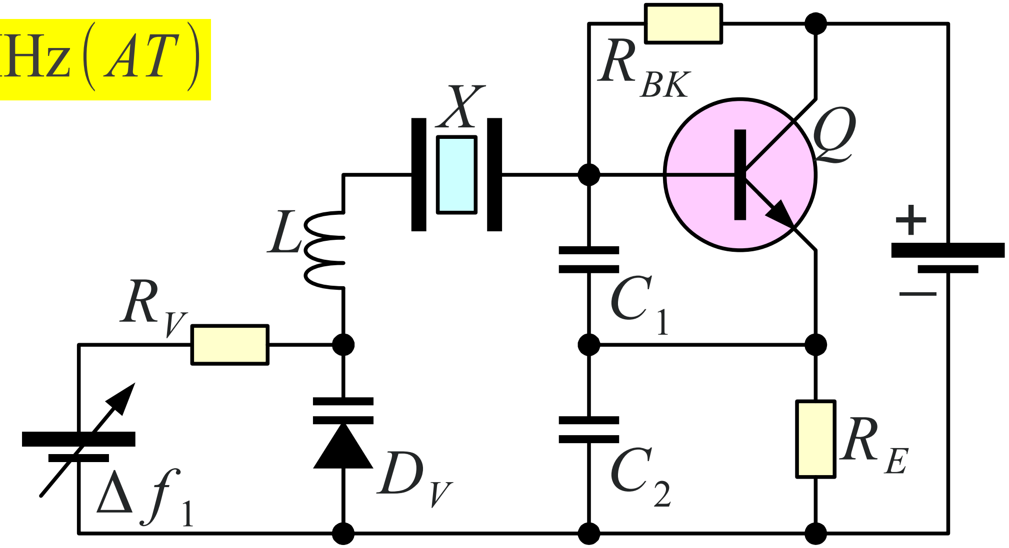
Crystal oscillators



Sticking – dirt hysteresis

$f_1 \approx 10 \ldots 20\text{MHz}\,(AT)$

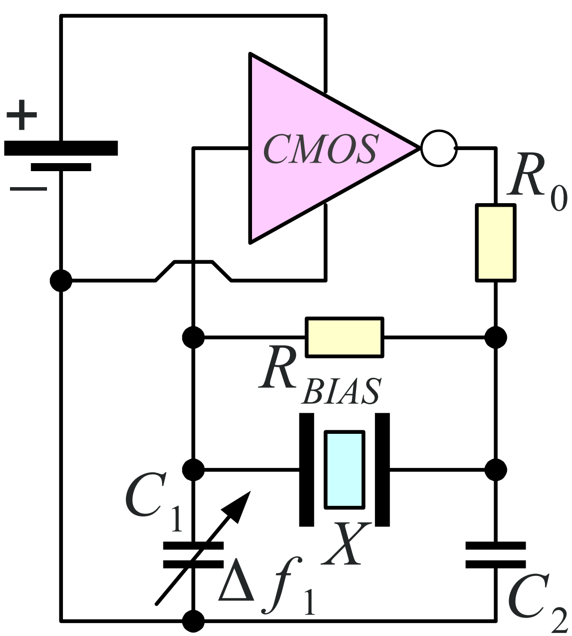


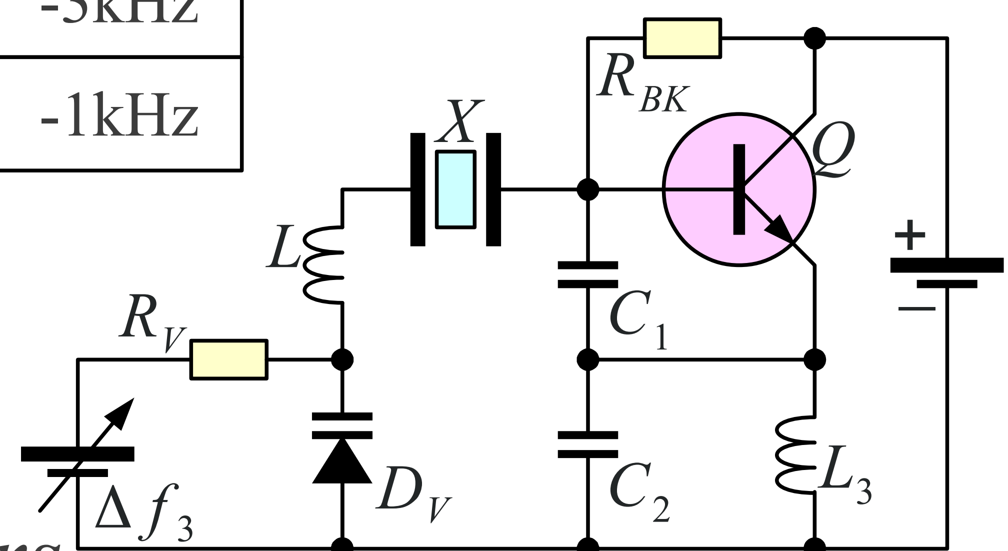


Adjustable crystal oscillator VXO

	C (variable)	L (variable)
Δf_1	+10kHz	-30kHz
Δf_3	+1kHz	-3kHz
Δf_5	+300Hz	-1kHz

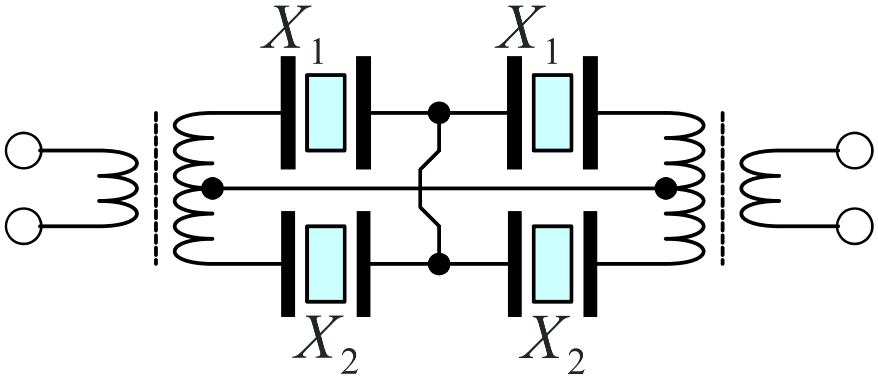
Voltage-adjustable crystal oscillator VCXO (temp. comp. TCXO)



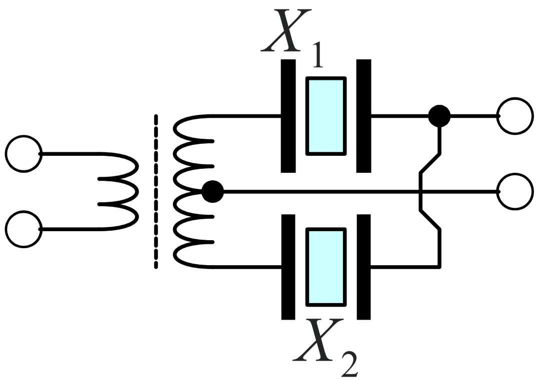


Adjustable crystal oscillators

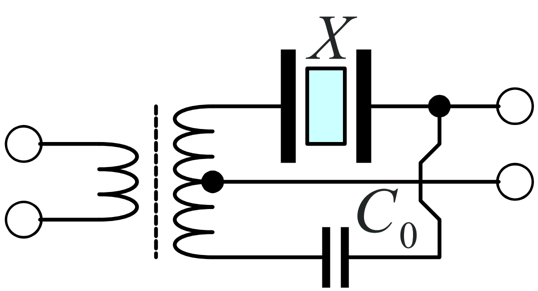
Crystal bandpass filters



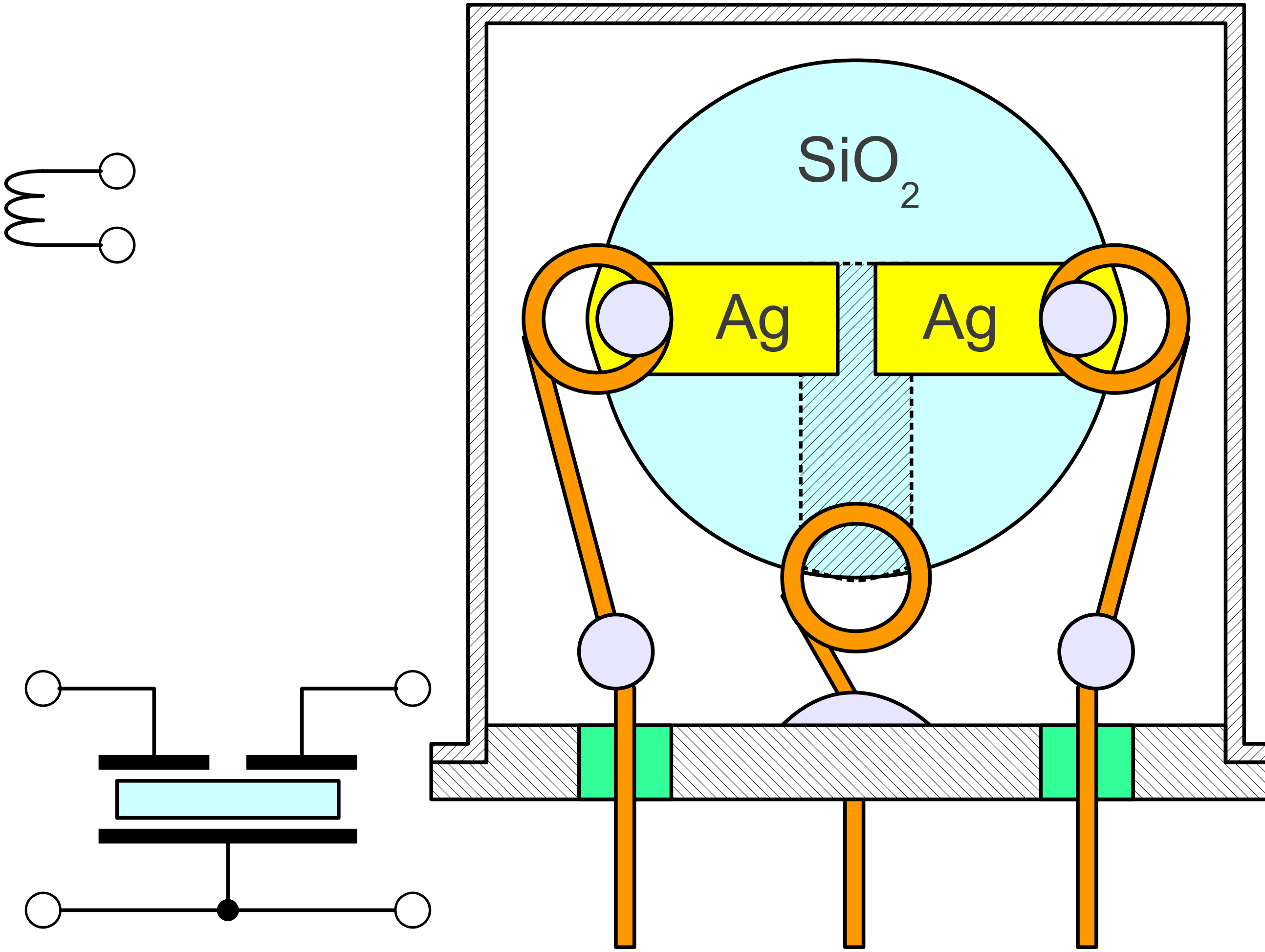
Double-bridge BPF



Bridge BPF

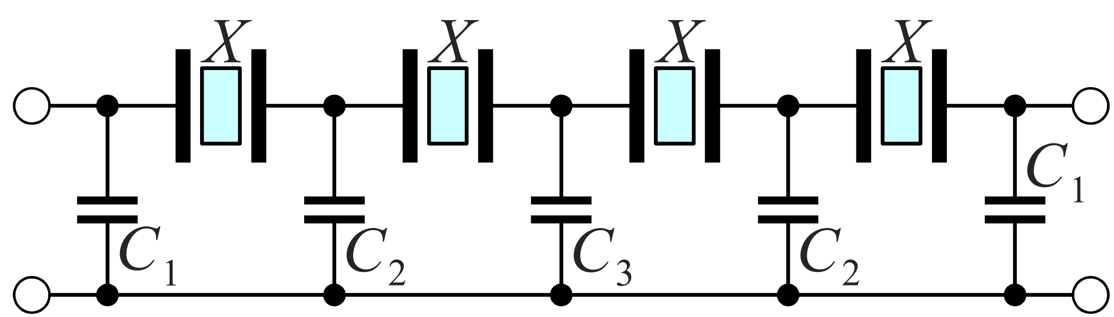


Simple BPF

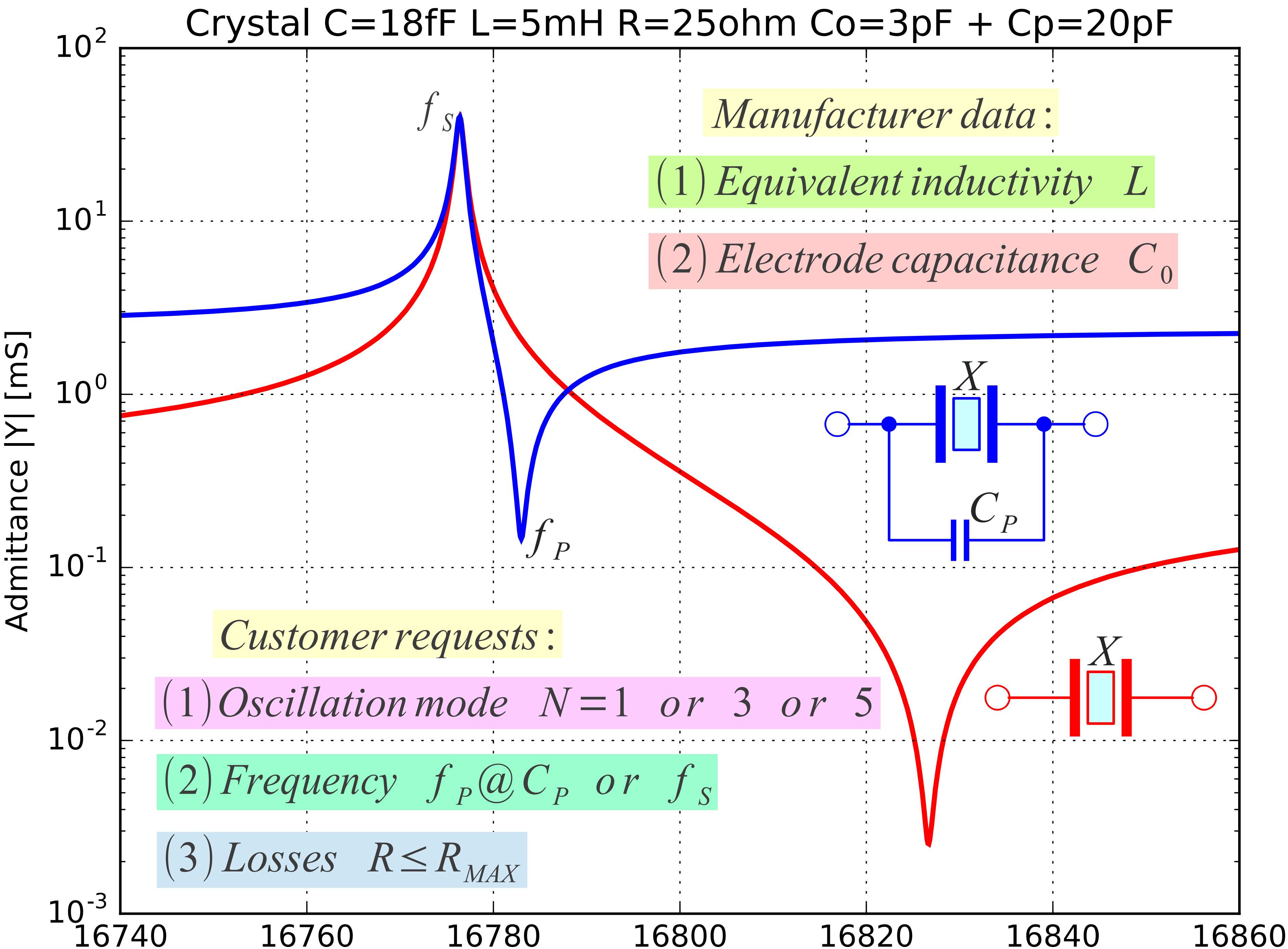


Monolithic BPF

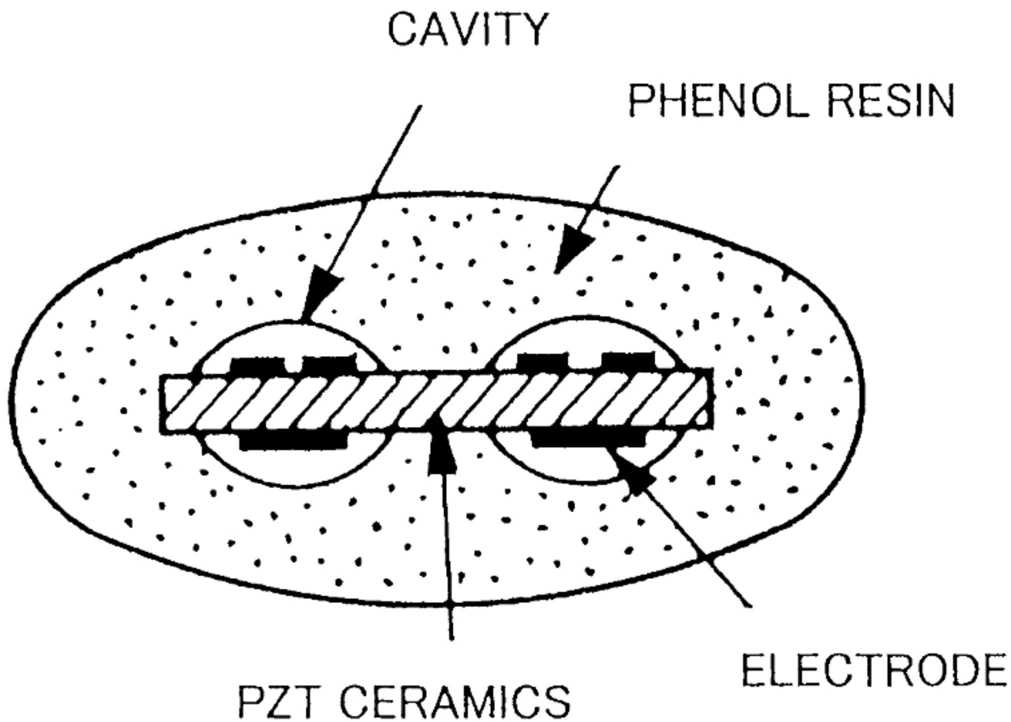
$200\text{Hz} \leq B \leq 50\text{kHz}$

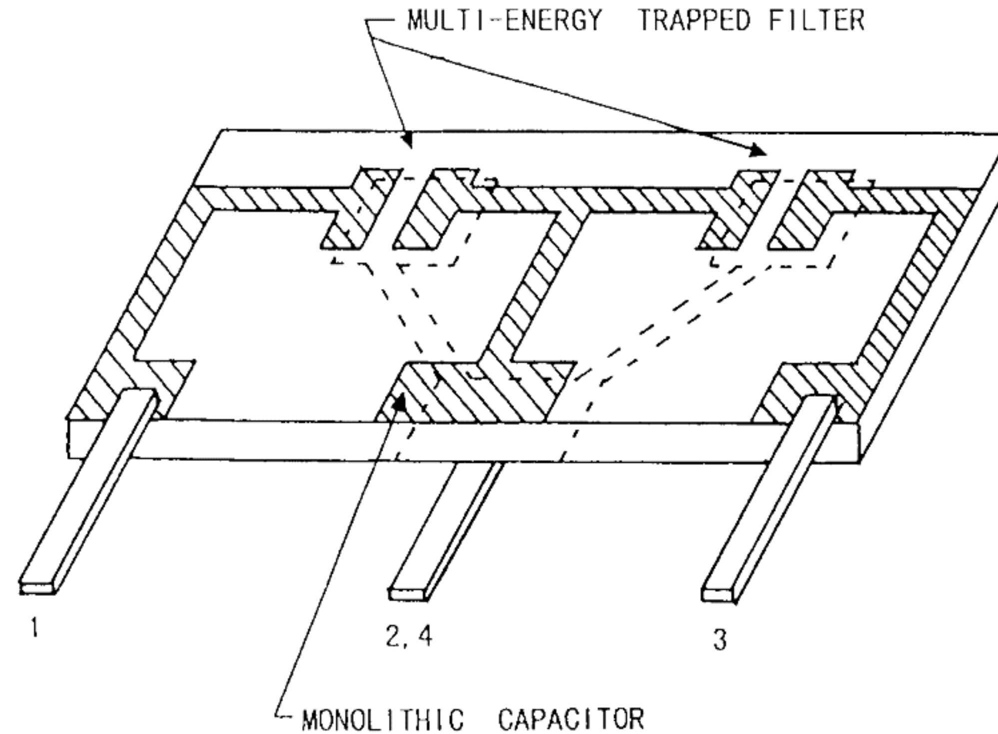


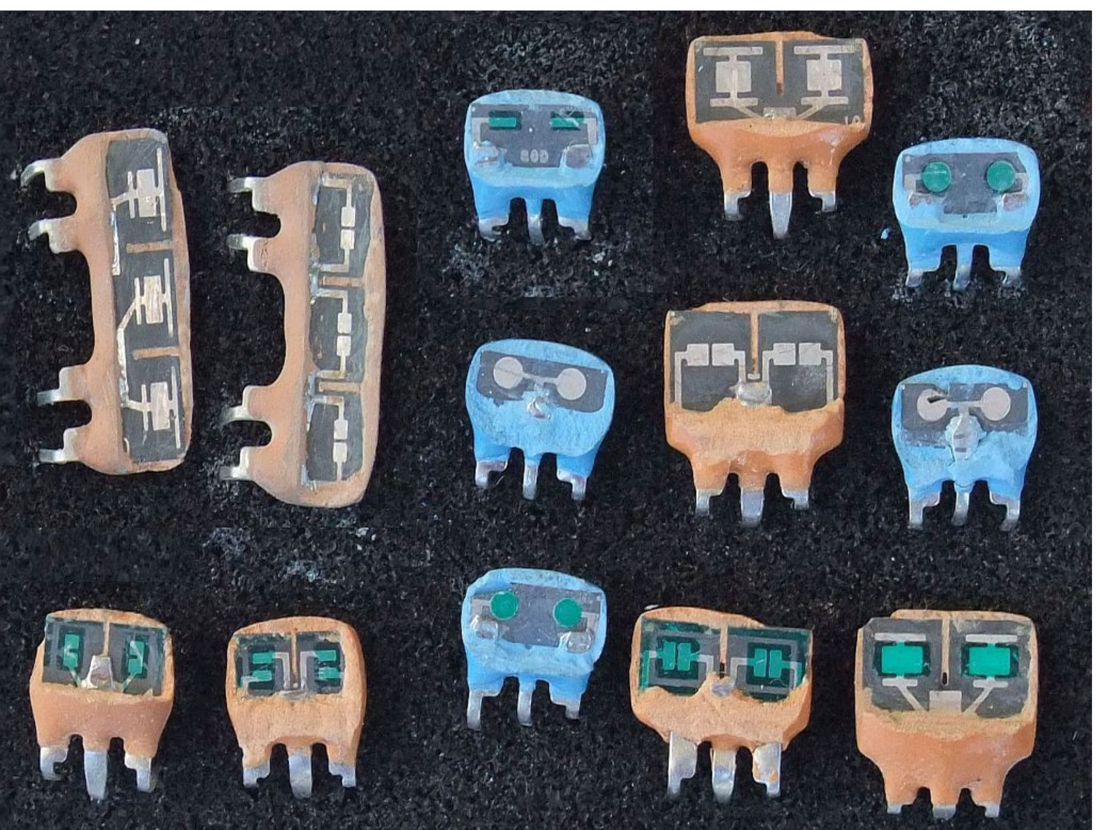
Ladder BPF

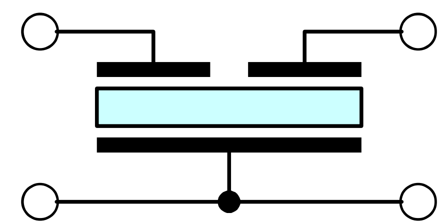


Crystal specification









$Pb\,Zr_x Ti_{1-x} O_3 \quad x \approx 0.52\,(PZT)$

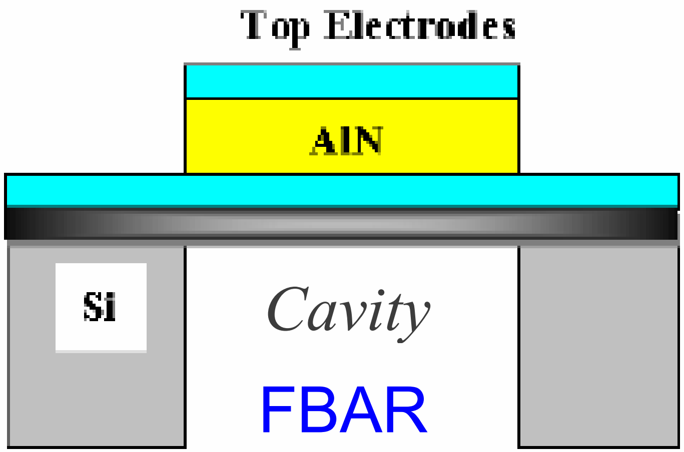
$v \approx 3\text{km/s} \ldots 4\text{km/s}$

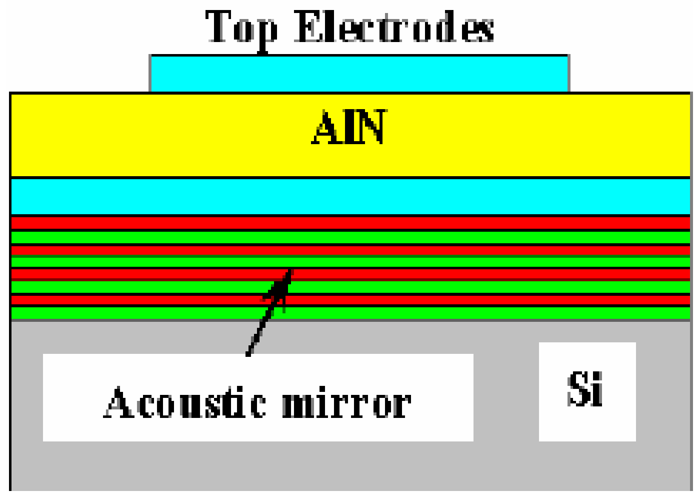
$Q \approx 1000 \quad @f = 10\text{MHz}$

Piezoceramics

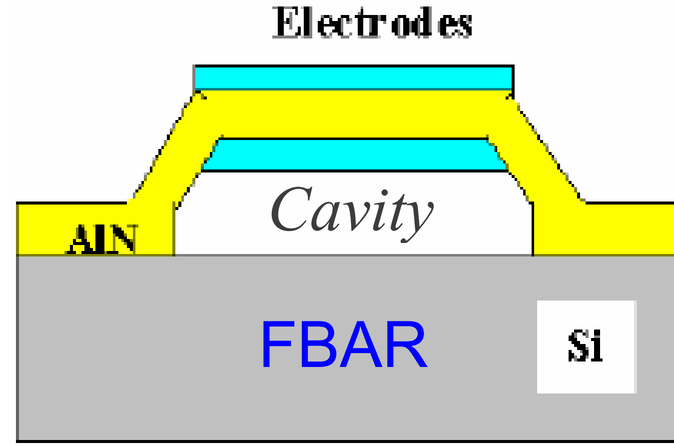
Film Bulk Acoustic Resonator (FBAR)

$Q \approx 2000 \quad @ f = 2\text{GHz}$

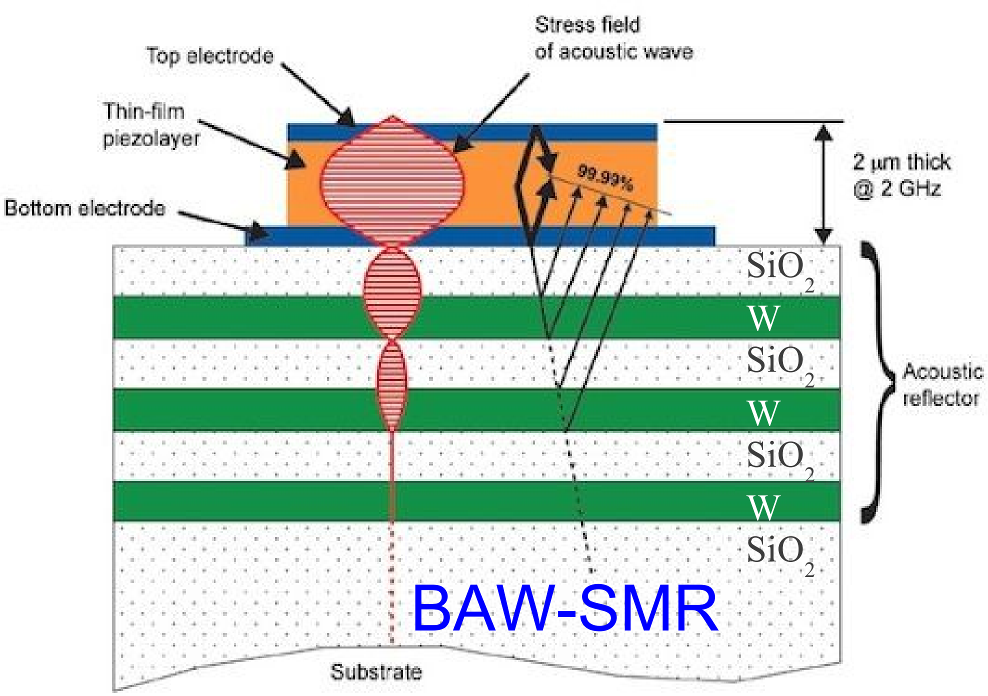




BAW-SMR

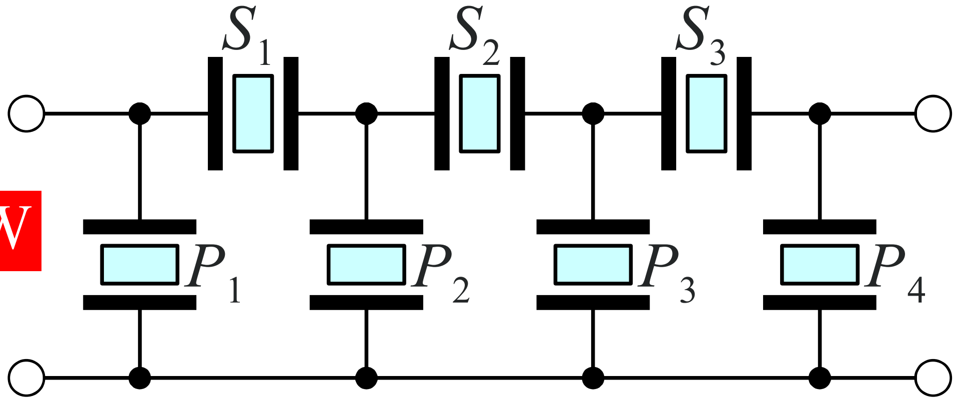


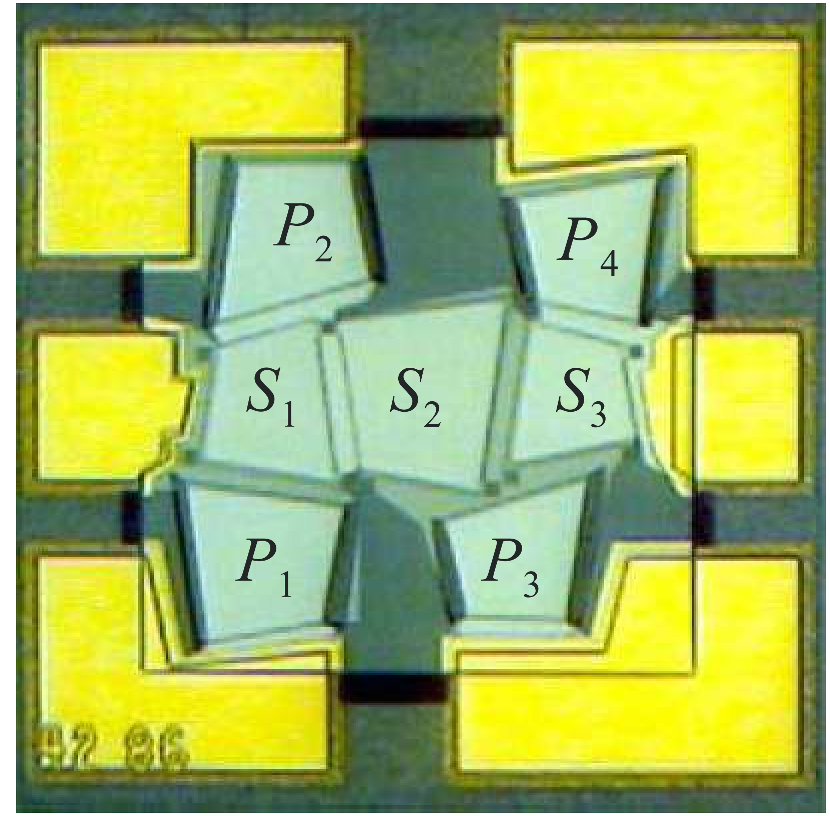
$v \approx 6\text{km/s} \ldots 11\text{km/s} \quad \textit{pressure wave } P$



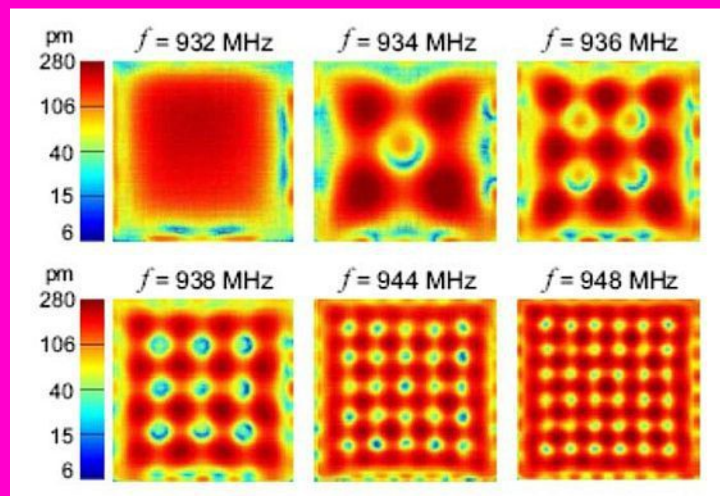
Material	Dielectric constant	Acoustic velocity (m/s)	Acoustic coupling	Acoustic loss dB/μs At 1 GHz
AlN (*new*)	8.5	10,400	0.17	~5
ZnO (*old*)	8.8	6,330	0.28	8.3

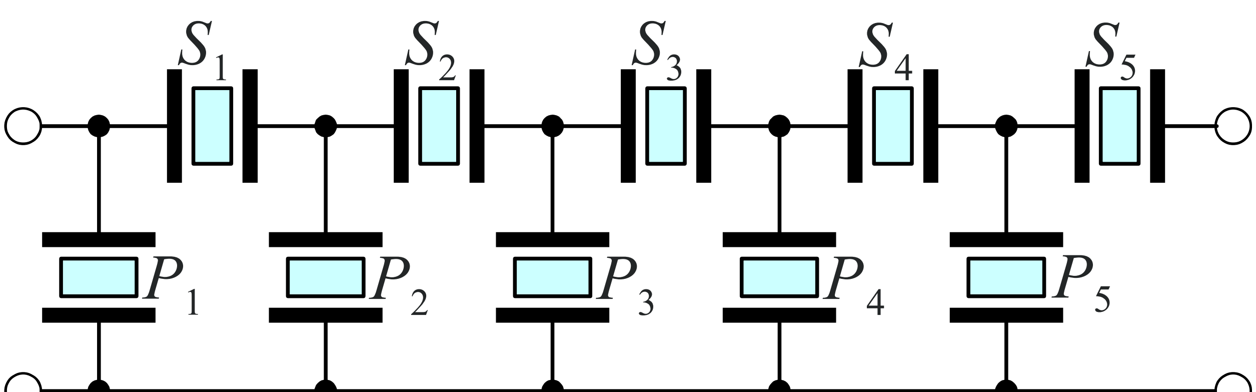
FBAR technologies

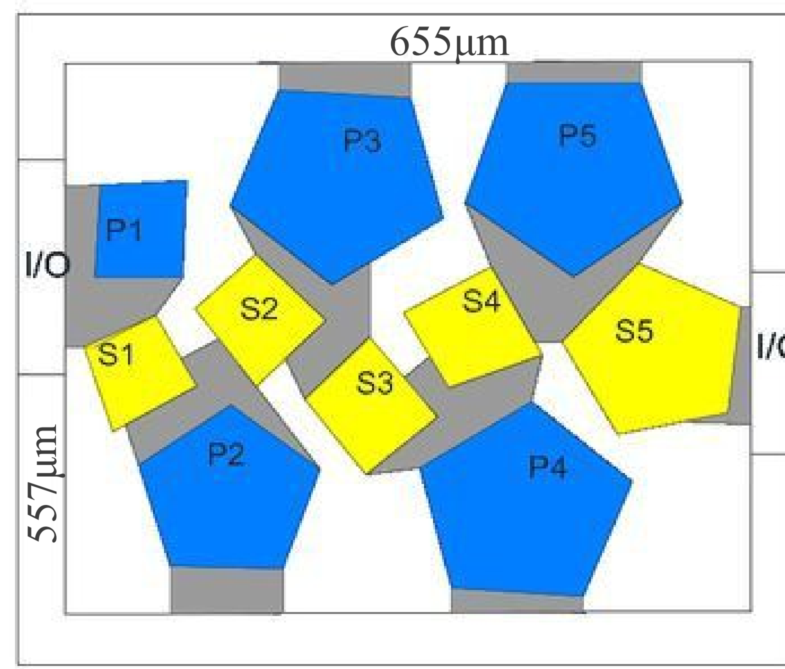




Anharmonics (transversal modes) of a square FBAR

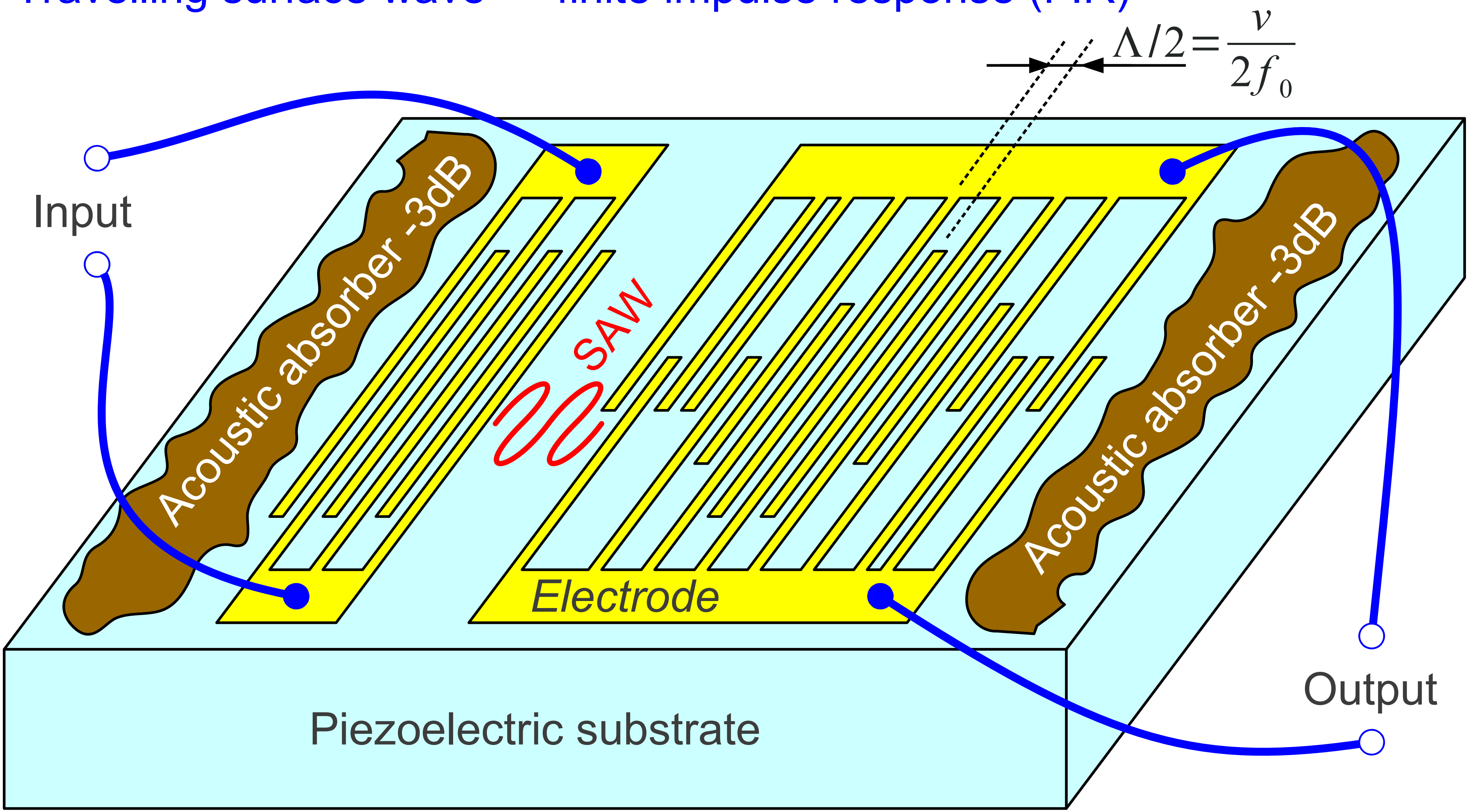






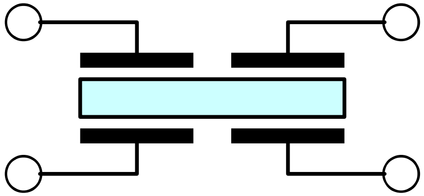
FBAR bandpass filters (IIR)

Travelling surface wave → finite impulse response (FIR)



Crystal substrate: SiO_2 (quartz) or $LiNbO_3$ or $LiTaO_3$ or $La_3Ga_5SiO_{14}$ (langasite)

stability ↔ coupling

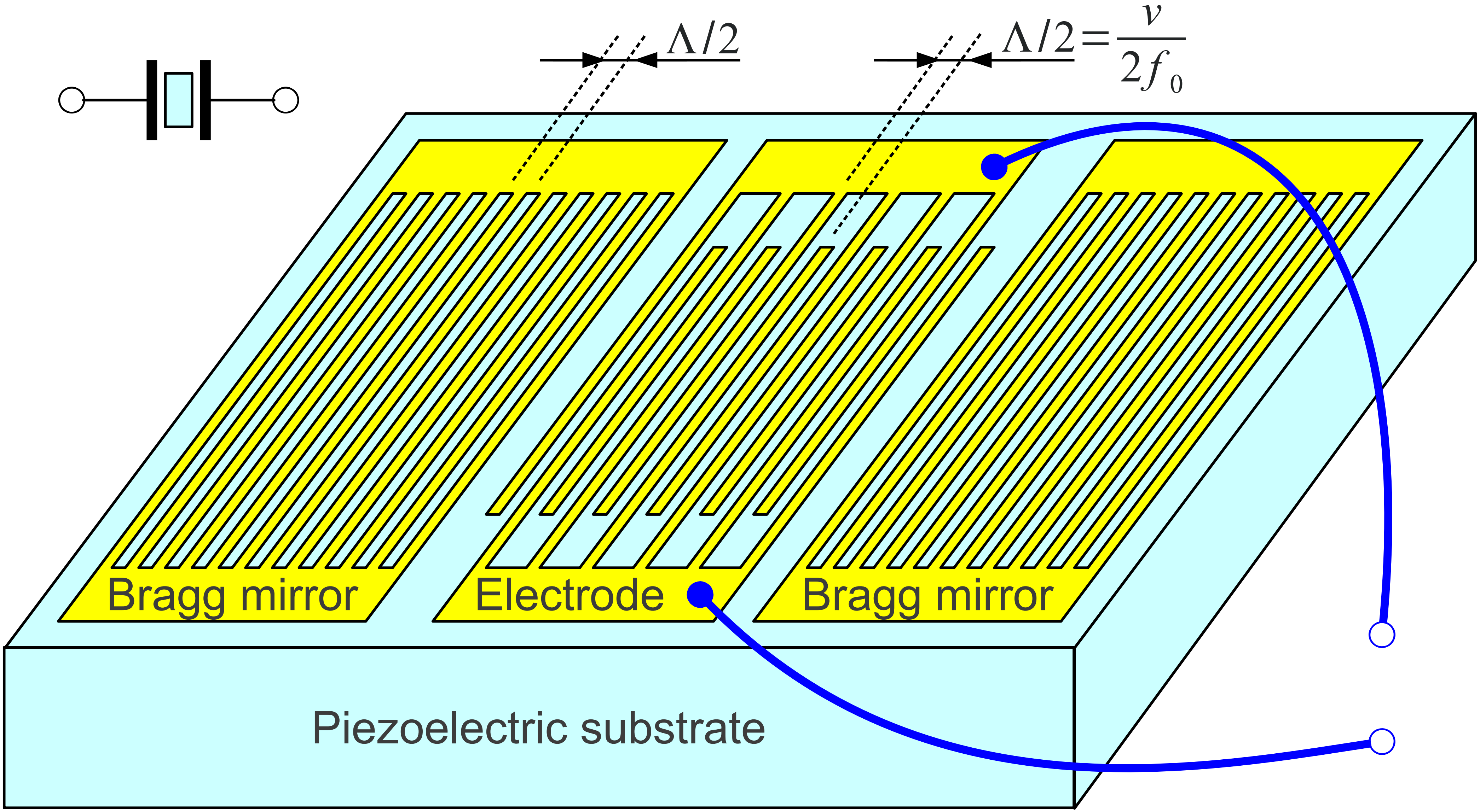


$v \approx 2\text{km/s} \ldots 5\text{km/s}$

SAW bandpass (FIR)

36MHz *SAW filter*

Standing surface wave → resonator ≡ infinite impulse response (IIR)



Crystal substrate: SiO_2 (quartz) or $LiNbO_3$ or $LiTaO_3$ or $La_3Ga_5SiO_{14}$ (langasite)

stability ↔ coupling

SAW resonator

$v \approx 2\text{km/s} \ldots 5\text{km/s}$