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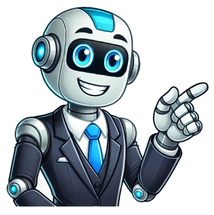

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Electronic oscillator circuit"Pull capacitor" redirects here. For resistors, see Pull-up resistor and Pull-down resistor."Padding capacitor" redirects here. For adjustable capacitors, see Trimmer capacitor.Crystal resonatorA miniature 16 MHz quartz crystal enclosed in a hermetically sealed HC-49/S package, used as the resonator in a crystal oscillator.Component typeElectromechanicalWorking principlePiezoelectricity, ResonanceInventorAlexander M. Nicholson, Walter Guyton CadyFirst produced1918Electronic symbolA crystal oscillator is an electronic oscillator circuit that uses a piezoelectric crystal as a frequency-selective element.[1][2][3] The oscillator frequency is often used to keep track of time, as in quartz wristwatches, to provide a stable clock signal for digital integrated circuits, and to stabilize frequencies for radio transmitters and receivers. The most common type of piezoelectric resonator used is a quartz crystal, so oscillator circuits incorporating them became known as crystal oscillators.[1] However, other piezoelectric materials including polycrystalline ceramics are used in similar circuits.A crystal oscillator relies on the slight change in shape of a quartz crystal under an electric field, a property known as inverse piezoelectricity. A voltage applied to the electrodes on the crystal causes it to change shape; when the voltage is removed, the crystal generates a small voltage as it elastically returns to its original shape. The quartz oscillates at a stable resonant frequency (relative to other low-priced oscillators) with frequency accuracy measured in parts per million (ppm). It behaves like an RLC circuit, but with a much higher Q factor (lower energy loss on each cycle of oscillation and higher frequency selectivity) than can be reliably achieved with discrete capacitors (C) and inductors (L), which suffer from parasitic resistance (R). Once a quartz crystal is adjusted to a particular frequency (which is affected by the mass of electrodes attached to the crystal, the orientation of the crystal, temperature and other factors), it maintains that frequency with high stability.[4]Quartz crystals are manufactured for frequencies from a few tens of kilohertz to hundreds of megahertz. As of 2003, around two billion crystals were manufactured annually.[5] Most are used for consumer devices such as wristwatches, clocks, radios, computers, and cellphones. However, in applications where small size and weight is needed crystals can be replaced by thin-film bulk acoustic resonators, specifically if ultra-high frequency (more than roughly 1.5GHz) resonance is needed. Quartz crystals are also found inside test and measurement equipment, such as counters, signal generators, and oscilloscopes.Quartz crystal resonator (left) and quartz crystal oscillator (right)A crystal oscillator is an electric oscillator type circuit that uses a piezoelectric resonator, a crystal, as its frequency-determining element. Crystal is the common term used in electronics for the frequency-determining component, a wafer of quartz crystal or ceramic with electrodes connected to it. A more accurate term for "crystal" is piezoelectric resonator. Crystals are also used in other types of electronic circuits, such as crystal filters.Piezoelectric resonators are sold as separate components for use in crystal oscillator circuits. They are also often incorporated in a single package with the crystal oscillator circuit.100 kHz crystal oscillators at the US National Bureau of Standards that served as the frequency standard for the United States in 1929Very early Bell Labs crystals from Vectron International CollectionPiezoelectricity was discovered by Jacques and Pierre Curie in 1880. Paul Langevin first investigated quartz resonators for use in sonar during World War I. The first crystal-controlled oscillator, using a crystal of Rochelle salt, was built in 1917 and patented[6] in 1918 by Alexander M. Nicholson at Bell Telephone Laboratories, although his priority was disputed by Walter Guyton Cady.[7] Cady built the first quartz crystal oscillator in 1921.[8]Other early innovators in quartz crystal oscillators include G. W. Pierce and Louis Essen.Quartz crystal oscillators were developed for high-stability frequency references during the 1920s and 1930s. Prior to crystals, radio stations controlled their frequency with tuned circuits, which could easily drift off frequency by 34kHz.[9] Since broadcast stations were assigned frequencies only 10kHz (Americas) or 9kHz (elsewhere) apart, interference between adjacent stations due to frequency drift was a common problem.[9] In 1925, Westinghouse installed a crystal oscillator in its flagship station KDKA,[9] and by 1926, quartz crystals were used to control the frequency of many broadcasting stations and were popular with amateur radio operators.[10] In 1928, Warren Marrison of Bell Laboratories developed the first quartz-crystal clock. With accuracies of up to 1 second in 30 years (30ms/y, or 0.95ns/s),[8] quartz clocks replaced precision pendulum clocks as the world's most accurate timekeepers until atomic clocks were developed in the 1950s. Using the early work at Bell Laboratories, American Telephone and Telegraph Company (AT&T) eventually established their Frequency Control Products division, later spun off and known today as Vectron International.[11]A number of firms started producing quartz crystals for electronic use during this time. Using what are now considered primitive methods, about 100,000 crystal units were produced in the United States during 1939. Through World War II crystals were made from natural quartz crystal, virtually all from Brazil. Shortages of crystals during the war caused by the demand for accurate frequency control of military and naval radios and radars spurred postwar research into culturing synthetic quartz, and by 1950 a hydrothermal process for growing quartz crystals on a commercial scale was developed at Bell Laboratories. By the 1970s virtually all crystals used in electronics were synthetic.In 1968, Juergen Staudte invented a photolithographic process for manufacturing quartz crystal oscillators while working at North American Aviation (now Rockwell) that allowed them to be made small enough for portable products like watches.[12]Although crystal oscillators still most commonly use quartz crystals, devices using other materials are becoming more common, such as ceramic resonators.Crystal oscillation modesA crystal is a solid in which the constituent atoms, molecules, or ions are packed in a regularly ordered, repeating pattern extending in all three spatial dimensions.Almost any object made of an elastic material could be used like a crystal, with appropriate transducers, since all objects have natural resonant frequencies of vibration. For example, steel is very elastic and has a high speed of sound. It was often used in mechanical filters before quartz. The resonant frequency depends on size, shape, elasticity, and the speed of sound in the material. High-frequency crystals are typically cut in the shape of a simple rectangle or circular disk. Low-frequency crystals, such as those used in digital watches, are typically cut in the shape of a tuning fork. For applications not needing very precise timing, a low-cost ceramic resonator is often used in place of a quartz crystal.When a crystal of quartz is properly cut and mounted, it can be made to distort in an electric field by applying a voltage to an electrode near or on the crystal. This property is known as inverse piezoelectricity. When the field is removed, the quartz generates an electric field as it returns to its previous shape, and this can generate a voltage. The result is that a quartz crystal behaves like an RLC circuit, composed of an inductor, capacitor and resistor, with a precise resonant frequency.Quartz has the further advantage that its elastic constants and its size change in such a way that the frequency dependence on temperature can be very low. The specific characteristics depend on the mode of vibration and the angle at which the quartz is cut (relative to its crystallographic axes).[13] Therefore, the resonant frequency of the plate, which depends on its size, does not change much. This means that a quartz clock, filter or oscillator remains accurate. For critical applications the quartz oscillator is mounted in a temperature-controlled container, called a crystal oven, and can also be mounted on shock absorbers to prevent perturbation by external mechanical vibrations.A quartz crystal can be modeled as an electrical network with low-impedance (series) and high-impedance (parallel) resonance points spaced closely together. Mathematically, using the Laplace transform, the impedance of this network can be written as:Schematic symbol and equivalent circuit for a quartz crystal in an oscillator Z (s) = (1 s C 1 + s L 1 + R 1) (1 s C 0) , {\displaystyle Z(s)=\left({{\frac {1}{s\cdot C_{1}}}+s\cdot L_{1}+R_{1}}\right)\left\|\left({\frac {1}{s\cdot C_{0}}}\right)\right.,} or Z (s) = s 2 + s R 1 L 1 + s 2 (s C 0) [s 2 + s R 1 L 1 + p 2] s = 1 L 1 C 1 , p = C 1 + C 0 L 1 C 1 C 0 = s 1 + C 1 C 0 s (1 + C 1 2 C 0) (C 0 C 1) {\displaystyle {\begin{aligned}Z(s)&={\frac {s^{2}+s{\frac {R_{1}}{L_{1}}}+{\omega _{\mathrm {s} }}^{2}}{\left(s\cdot C_{0}\right)\left[s^{2}+s{\frac {R_{1}}{L_{1}}}+{\omega _{\mathrm {p} }}^{2}\right]}}\\[2pt]\Rightarrow \omega _{\mathrm {s} }&={\frac {1}{\sqrt {L_{1}\cdot C_{1}}}},\quad \omega _{\mathrm {p} }={\sqrt {\frac {C_{1}+C_{0}}{L_{1}\cdot C_{1}\cdot C_{0}}}}=\omega _{\mathrm {s} }{\sqrt {1+{\frac {C_{1}}{C_{0}}}}}\approx \omega _{\mathrm {s} }\left(1+{\frac {C_{1}}{2C_{0}}}\right)\quad \left(C_{0}\gg C_{1}\right)\end{aligned}}} where s {\displaystyle s} is the complex frequency (s = j {\displaystyle s=j\omega }), s {\displaystyle \omega _{\mathrm {s} }} is the series resonant angular frequency, and p {\displaystyle \omega _{\mathrm {p} }} is the parallel resonant angular frequency.Adding capacitance across a crystal causes the (parallel) resonant frequency to decrease. Adding inductance across a crystal causes the (parallel) resonant frequency to increase. These effects can be used to adjust the frequency at which a crystal oscillates. Crystal manufacturers normally cut and trim their crystals to have a specified resonant frequency with a known "load" capacitance added to the crystal. For example, a crystal intended for a 6pF load has its specified parallel resonant frequency when a 6.0pF capacitor is placed across it. Without the load capacitance, the resonant frequency is higher.A quartz crystal provides both series and parallel resonance. The series resonance is a few kilohertz lower than the parallel one. Crystals below 30MHz are generally operated between series and parallel resonance, which means that the crystal appears as an inductive reactance in operation, this inductance forming a parallel resonant circuit with externally connected parallel capacitance. Frequency response of a 100kHz crystal, showing series and parallel resonanceAny small additional capacitance in parallel with the crystal pulls the frequency lower. Moreover, the effective inductive reactance of the crystal can be reduced by adding a capacitor in series with the crystal. This latter technique can provide a useful method of trimming the oscillatory frequency within a narrow range; in this case inserting a capacitor in series with the crystal raises the frequency of oscillation. For a crystal to operate at its specified frequency, the electronic circuit has to be exactly that specified by the crystal manufacturer. Note that these points imply a subtlety concerning crystal oscillators in this frequency range: the crystal does not usually oscillate at precisely either of its resonant frequencies.Crystals above 30MHz (up to >200MHz) are generally operated at series resonance where the impedance appears at its minimum and equal to the series resistance. For these crystals the series resistance is specified (10 MHz)The most common cut, developed in 1934. The plate contains the crystal's xaxis and is inclined by 3515 from the z(optical) axis. The frequency-temperature curve is a sine-shaped curve with inflection point at around 25~35 C . Has frequency constant 1.661MHzmm.[52] Most (estimated over 90%) of all crystals are this variant.[53] Used for oscillators operating in wider temperature range, for a frequency range of 500kHz200MHz; also used in oven-controlled oscillators.[54] Sensitive to mechanical stresses, whether caused by external forces or by temperature gradients. Thickness-shear crystals typically operate in fundamental mode at 130MHz, 3rd overtone at 3090MHz, and 5th overtone at 90150MHz;[55] according to other source they can be made for fundamental mode operation up to 300MHz, though that mode is usually used only to 100MHz[56] and according to yet another source the upper limit for fundamental frequency of the ATcut is limited to 40MHz for small diameter blanks.[52] Can be manufactured either as a conventional round disk, or as a strip resonator; the latter allows much smaller size. The thickness of the quartz blank is about (1.661mm)/(frequency in MHz), with the frequency somewhat shifted by further processing.[57] The third overtone is about 3times the fundamental frequency; the overtones are higher than the equivalent multiple of the fundamental frequency by about 25kHz per overtone. Crystals designed for operating in overtone modes have to be specially processed for plane parallelism and surface finish for the best performance at a given overtone frequency.[49]SC500kHz 200MHzthickness shear3515, 2154A special cut (Stress Compensated) developed in 1974, is a double-rotated cut (3515 and 2154) for oven-stabilized oscillators with low phase noise and good aging characteristics. Less sensitive to mechanical stresses. Has faster warm-up speed, higher Q, better close-in phase noise, less sensitivity to spatial orientation against the vector of gravity, and less sensitivity to vibrations.[58] Its frequency constant is 1.797MHzmm. Coupled modes are worse than the ATcut, resistance tends to be higher; much more care is required to convert between overtones. Operates at the same frequencies as the ATcut. The frequency-temperature curve is a third order downward parabola with inflection point at 95C and much lower temperature sensitivity than the AT cut. Suitable for OCXOs in e.g. space and GPS systems. Less available than ATcut, more difficult to manufacture; the order-of-magnitude improvement of parameters is traded for an order of magnitude tighter crystal orientation tolerances.[59] Aging characteristics are 2~3times better than of the ATcuts. Less sensitive to drive levels. Far fewer activity dips. Less sensitive to plate geometry. Requires an oven, does not operate well at ambient temperatures as the frequency rapidly falls off at lower temperatures. Has several times lower motional capacitance than the corresponding ATcut, reducing the possibility to adjust the crystal frequency by attached capacitor; this restricts usage in conventional TCXO and VCXO devices, and other applications where the frequency of the crystal has to be adjustable.[60][58] The temperature coefficients for the fundamental frequency is different than for its third overtone; when the crystal is driven to operate on both frequencies simultaneously, the resulting beat frequency can be used for temperature sensing in e.g. microcomputer-compensated crystal oscillators. Sensitive to electric fields. Sensitive to air damping, to obtain optimum Q it has to be packaged in vacuum.[45] Temperature coefficient for bmode is 25 ppm/C , for dual mode 80 to over 100 ppm/C .[61]BT500kHz 200MHzthickness shear (bmode, fast quasi-shear)498, 0A special cut, similar to ATcut, except the plate is cut at 49 from the zaxis. Operates in thickness shear mode, in bmode (fast quasi-shear). It has well known and repeatable characteristics.[62] Has frequency constant 2.536 MHzmm. Has poorer temperature characteristics than the ATcut. Due to the higher frequency constant, can be used for crystals with higher frequencies than the ATcut, up to over 50 MHz . [52]ITthickness shearA special cut, a double-rotated cut with improved characteristics for oven-stabilized oscillators. Operates in thickness shear mode. The frequency-temperature curve is a third order downward parabola with inflection point at 78 C . Rarely used. Has similar performance and properties to the SCcut, more suitable for higher temperatures.FCthickness shearA special cut, a double-rotated cut with improved characteristics for oven-stabilized oscillators. Operates in thickness shear mode. The frequency-temperature curve is a third order downward parabola with inflection point at 52 C . Rarely used. Employed in oven-controlled oscillators; the oven can be set to lower temperature than for the AT / IT / SCcuts, to the beginning of the flat part of the temperature-frequency curve (which is also broader than of the other cuts); when the ambient temperature reaches this region, the oven switches off and the crystal operates at the ambient temperature, while maintaining reasonable accuracy. This cut therefore combines the power saving feature of allowing relatively low oven temperature with reasonable stability at higher ambient temperatures.[63]AKthickness sheara double rotated cut with better temperature-frequency characteristics than AT and BTcuts and with higher tolerance to crystallographic orientation than the AT, BT, and SCcuts (calculated to be a factor 50 against a standard ATcut). It operates in thickness-shear mode.[59]CT300 900kHzface shear38, 0The frequency-temperature curve is a downward parabola.DT75 800kHzface shear52, 0Similar to CTcut. The frequency-temperature curve is a downward parabola. The temperature coefficient is lower than the CTcut; where the frequency range permits, DT is preferred over CT.[52]SLface-shear57, 0GT100kHz 3MHzwidth-extensional517Its temperature coefficient between 25 ... +75C is near-zero, due to cancelling effect between two modes.[52]E, 5X50 250kHzlongitudinalHas reasonably low temperature coefficient, widely used for low-frequency crystal filters.[52]MT40 200kHzlongitudinalET6630FT57NT8 130kHzlength-width flexure (bending)XY, tuning fork3 85kHzlength-width flexureThe dominant low-frequency crystal, as it is smaller than other low-frequency cuts, less expensive, has low impedance and low C0/ C1 ratio. The chief application is the 32.768kHz RTCcrystal. Its second overtone is about six times the fundamental frequency.[49]H8 130kHzlength-width flexureUsed extensively for wideband filters. The temperature coefficient is linear.J1 12kHzlength-thickness flexure] cut is made of two quartz plates bonded together, selected to produce out of phase motion for a given electrical field.RTA double rotated cut.SBTCA double rotated cut.TSA double rotated cut.X30A double rotated cut.LCthickness shear11.17 / 9.39A double rotated cut ("linear coefficient") with a linear temperature-frequency response; can be used as a sensor in crystal thermometers.[64] Temperature coefficient is 35.4 ppm/C .[61]AC31Temperature-sensitive, can be used as a sensor. Single mode with steep frequency-temperature characteristics.[65] Temperature coefficient is 20 ppm/C .[61]BC60Temperature-sensitive.[65]NLSCTemperature-sensitive.[65] Temperature coefficient is about 14 ppm/C .[61]YTemperature-sensitive, can be used as a sensor. Single mode with steep frequency-temperature characteristics.[65] The plane of the plate is perpendicular to the yaxis of the crystal.[66] Also called parallel or 30-degree. Temperature coefficient is about 90 ppm/C .[61]XUsed in one of the first crystal oscillators in 1921 by W.G. Cady, and as a 50kHz oscillator in the first crystal clock by Horton and Marrison in 1927.[67] The plane of the plate is perpendicular to the xaxis of the crystal. Also called perpendicular, normal, Curie, zero-angle, or ultrasonic.[68]The letter T in the cut name marks a temperature-compensated cut a cut oriented in a way that the temperature coefficients of the lattice are minimal; the FC and SCcuts are also temperature-compensated.The high frequency cuts are mounted by their edges, usually on springs; the stiffness of the spring has to be optimal, as if it is too stiff, mechanical shocks could be transferred to the crystal and cause it to break, and too little stiffness may allow the crystal to collide with the inside of the package when subjected to a mechanical shock, and break. Strip resonators, usually ATcuts, are smaller and therefore less sensitive to mechanical shocks. At the same frequency and overtone, the strip has less pullability, higher resistance, and higher temperature coefficient.[69]The low frequency cuts are mounted at the nodes where they are virtually motionless; thin wires are attached at such points on each side between the crystal and the leads. The large mass of the crystal suspended on the thin wires makes the assembly sensitive to mechanical shocks and vibrations.[52]The crystals are usually mounted in hermetically sealed glass or metal cases, filled with a dry and inert atmosphere, usually vacuum, nitrogen, or helium. Plastic housings can be used as well, but those are not hermetic and another secondary sealing has to be built around the crystal.Several resonator configurations are possible, in addition to the classical way of directly attaching leads to the crystal. E.g. the BVA resonator (Botier Vieillissement Amlior, Enclosure with Improved Aging),[70][unreliable source?] developed in 1976; the parts that influence the vibrations are machined from a single crystal (which reduces the mounting stress), and the electrodes are deposited not on the resonator itself but on the inner sides of two condenser discs made of adjacent slices of the quartz from the same bar, forming a three-layer sandwich with no stress between the electrodes and the vibrating element. The gap between the electrodes and the resonator act as two small series capacitors, making the crystal less sensitive to circuit influences.[71][unreliable source?] The architecture eliminates the effects of the surface contacts between the electrodes, the constraints in the mounting connections, and the issues related to ion migration from the electrodes into the lattice of the vibrating element.[72] The resulting configuration is rugged, resistant to shock and vibration, resistant to acceleration and ionizing radiation, and has improved aging characteristics. ATcut is usually used, though SCcut variants exist as well. BVA resonators are often used in spacecraft applications.[73]In the 1930s to 1950s, it was fairly common for people to adjust the frequency of the crystals by manual grinding. The crystals were ground using a fine abrasive slurry, or even a toothpaste, to increase their frequency. A slight decrease by 12kHz when the crystal was overground was possible by marking the crystal face with a pencil lead, at the cost of a lowered Q.[74]The frequency of the crystal is slightly adjustable ("pullable") by modifying the attached capacitances. A varactor, a diode with capacitance depending on applied voltage, is often used in voltage-controlled crystal oscillators, VCXO. The crystal cuts are usually AT or rarely SC, and operate in fundamental mode; the amount of available frequency deviation is inversely proportional to the square of the overtone number, so a third overtone has only one-ninth of the pullability of the fundamental mode. SCcuts, while more stable, are significantly less pullable.[75]On electrical schematic diagrams, crystals are designated with the class letter Y (Y1, Y2, etc.). Oscillators, whether they are crystal oscillators or others, are designated with the class letter G (G1, G2, etc.).[76][77] Crystals may also be designated on a schematic with X or XTAL (a phonetic abbreviation, comparable to using Xmas for Christmas), or a crystal oscillator with XO.Crystal oscillator types and their abbreviations:ATCXO Analog temperature controlled crystal oscillatorCDXO Calibrated dual crystal oscillatorDTCXO Digital temperature compensated crystal oscillatorEMXO Evacuated miniature crystal oscillatorGPSDO Global positioning system disciplined oscillatorMCXO Microcomputer-compensated crystal oscillatorOCVCXO oven-controlled voltage-controlled crystal oscillatorOCXO Oven-controlled crystal oscillatorRbXO Rubidium crystal oscillators (RbXO), a crystal oscillator (can be an MCXO) synchronized with a built-in rubidium standard which is run only occasionally to save powerTCVCXO Temperature-compensated voltage-controlled crystal oscillatorTCXO Temperature-compensated crystal oscillatorTMXO Tactical miniature crystal oscillator[67]TSXO Temperature-sensing crystal oscillator, an adaptation of the TCXOVCTCXO Voltage-controlled temperature-compensated crystal oscillatorVCXO Voltage-controlled crystal oscillatorClock generatorClock drift Clock drift measurements of crystal oscillators can be used to build random number generators.Crystal filterErhard Kietz, who worked on electronic tuning forks and with quartz crystals for precise signal frequenciesIssac Koga inventor of the temperature-stable R1 Koga cutPierce oscillatorThin-film thickness monitorVariable-frequency oscillator (VFO)^ a b Graf, Rudolf F. 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Retrieved 2009-03-31.Distortions in Crystal OscillatorsQuartz crystal resonators and oscillatorsMultipage summary of quartz crystals & their oscillators, filters, etcRetrieved from " Electronic Component Knowledge From the ticking of your wristwatch to the heartbeat of complex digital systems, the quartz crystal oscillator plays an indispensable role. This seemingly simple component, based on the piezoelectric effect, provides a stable and accurate frequency reference cruc

due to frequency drift was a common problem.[9] In 1925, Westinghouse installed a crystal oscillator in its flagship station KDKA,[9] and by 1926, quartz crystals were used to control the frequency of many broadcasting stations and were popular with amateur radio operators.[10] In 1928, Warren Marrison of Bell Laboratories developed the first quartz-crystal clock. With accuracies of up to 1 second in 30 years (30ms/y, or 0.95ns/s),[8] quartz clocks replaced precision pendulum clocks as the world's most accurate timekeepers until atomic clocks were developed in the 1950s. Using the early work at Bell Laboratories, American Telephone and Telegraph Company (AT&T) eventually established their Frequency Control Products division, later spun off and known today as Vectron International.[11]A number of firms started producing quartz crystals for electronic use during this time. Using what are now considered primitive methods, about 100,000 crystal units were produced in the United States during 1939. Through World War II crystals were made from natural quartz crystal, virtually all from Brazil. Shortages of crystals during the war caused by the demand for accurate frequency control of military and naval radios and radars spurred postwar research into culturing synthetic quartz, and by 1950 a hydrothermal process for growing quartz crystals on a commercial scale was developed at Bell Laboratories. By the 1970s virtually all crystals used in electronics were synthetic.In 1968, Juergen Staudte invented a photolithographic process for manufacturing quartz crystal oscillators while working at North American Aviation (now Rockwell) that allowed them to be made small enough for portable products like watches.[12]Although crystal oscillators still most commonly use quartz crystals, devices using other materials are becoming more common, such as ceramic resonators.Crystal oscillation modesA crystal is a solid in which the constituent atoms, molecules, or ions are packed in a regularly ordered, repeating pattern extending in all three spatial dimensions.Almost any object made of an elastic material could be used like a crystal, with appropriate transducers, since all objects have natural resonant frequencies of vibration. For example, steel is very elastic and has a high speed of sound. It was often used in mechanical filters before quartz. The resonant frequency depends on size, shape, elasticity, and the speed of sound in the material. High-frequency crystals are typically cut in the shape of a simple rectangle or circular disk. Low-frequency crystals, such as those used in digital watches, are typically cut in the shape of a tuning fork. For applications not needing very precise timing, a low-cost ceramic resonator is often used in place of a quartz crystal.When a crystal of quartz is properly cut and mounted, it can be made to distort in an electric field by applying a voltage to an electrode near or on the crystal. This property is known as inverse piezoelectricity. When the field is removed, the quartz generates an electric field as it returns to its previous shape, and this can generate a voltage. The result is that a quartz crystal behaves like an RLC circuit, composed of an inductor, capacitor and resistor, with a precise resonant frequency.Quartz has the further advantage that its elastic constants and its size change in such a way that the frequency dependence on temperature can be very low. The specific characteristics depend on the mode of vibration and the angle at which the quartz is cut (relative to its crystallographic axes).[13] Therefore, the resonant frequency of the plate, which depends on its size, does not change much. This means that a quartz clock, filter or oscillator remains accurate. For critical applications the quartz oscillator is mounted in a temperature-controlled container, called a crystal oven, and can also be mounted on shock absorbers to prevent perturbation by external mechanical vibrations.A quartz crystal can be modeled as an electrical network with low-impedance (series) and high-impedance (parallel) resonance points spaced closely together. Mathematically, using the Laplace transform, the impedance of this network can be written as:Schematic symbol and equivalent circuit for a quartz crystal in an oscillator Z (s) = (1 s C 1 + s L 1 + R 1) (1 s C 0) , {\displaystyle Z(s)=\left({{\frac {1}{s\cdot C_{1}}}+s\cdot L_{1}+R_{1}}\right)\left\|\left({\frac {1}{s\cdot C_{0}}}\right)\right.,} or Z (s) = s 2 + s R 1 L 1 + s 2 (s C 0) [s 2 + s R 1 L 1 + p 2] s = 1 L 1 C 1 , p = C 1 + C 0 L 1 C 1 C 0 = s 1 + C 1 C 0 s (1 + C 1 2 C 0) (C 0 C 1) {\displaystyle {\begin{aligned}Z(s)&={\frac {s^{2}+s{\frac {R_{1}}{L_{1}}}+{\omega _{\mathrm {s} }}^{2}}{\left(s\cdot C_{0}\right)\left[s^{2}+s{\frac {R_{1}}{L_{1}}}+{\omega _{\mathrm {p} }}^{2}\right]}}\\[2pt]\Rightarrow \omega _{\mathrm {s} }&={\frac {1}{\sqrt {L_{1}\cdot C_{1}}}},\quad \omega _{\mathrm {p} }={\sqrt {\frac {C_{1}+C_{0}}{L_{1}\cdot C_{1}\cdot C_{0}}}}=\omega _{\mathrm {s} }{\sqrt {1+{\frac {C_{1}}{C_{0}}}}}\approx \omega _{\mathrm {s} }\left(1+{\frac {C_{1}}{2C_{0}}}\right)\quad \left(C_{0}\gg C_{1}\right)\end{aligned}}} where s {\displaystyle s} is the complex frequency (s = j {\displaystyle s=j\omega }), s {\displaystyle \omega _{\mathrm {s} }} is the series resonant angular frequency, and p {\displaystyle \omega _{\mathrm {p} }} is the parallel resonant angular frequency.Adding capacitance across a crystal causes the (parallel) resonant frequency to decrease. Adding inductance across a crystal causes the (parallel) resonant frequency to increase. These effects can be used to adjust the frequency at which a crystal oscillates. Crystal manufacturers normally cut and trim their crystals to have a specified resonant frequency with a known "load" capacitance added to the crystal. For example, a crystal intended for a 6pF load has its specified parallel resonant frequency when a 6.0pF capacitor is placed across it. Without the load capacitance, the resonant frequency is higher.A quartz crystal provides both series and parallel resonance. The series resonance is a few kilohertz lower than the parallel one. Crystals below 30MHz are generally operated between series and parallel resonance, which means that the crystal appears as an inductive reactance in operation, this inductance forming a parallel resonant circuit with externally connected parallel capacitance. Frequency response of a 100kHz crystal, showing series and parallel resonanceAny small additional capacitance in parallel with the crystal pulls the frequency lower. Moreover, the effective inductive reactance of the crystal can be reduced by adding a capacitor in series with the crystal. This latter technique can provide a useful method of trimming the oscillatory frequency within a narrow range; in this case inserting a capacitor in series with the crystal raises the frequency of oscillation. For a crystal to operate at its specified frequency, the electronic circuit has to be exactly that specified by the crystal manufacturer. Note that these points imply a subtlety concerning crystal oscillators in this frequency range: the crystal does not usually oscillate at precisely either of its resonant frequencies.Crystals above 30MHz (up to >200MHz) are generally operated at series resonance where the impedance appears at its minimum and equal to the series resistance. For these crystals the series resistance is specified (10 MHz)The most common cut, developed in 1934. The plate contains the crystal's xaxis and is inclined by 3515 from the z(optical) axis. The frequency-temperature curve is a sine-shaped curve with inflection point at around 25~35 C . Has frequency constant 1.661MHzmm.[52] Most (estimated over 90%) of all crystals are this variant.[53] Used for oscillators operating in wider temperature range, for a frequency range of 500kHz200MHz; also used in oven-controlled oscillators.[54] Sensitive to mechanical stresses, whether caused by external forces or by temperature gradients. Thickness-shear crystals typically operate in fundamental mode at 130MHz, 3rd overtone at 3090MHz, and 5th overtone at 90150MHz;[55] according to other source they can be made for fundamental mode operation up to 300MHz, though that mode is usually used only to 100MHz[56] and according to yet another source the upper limit for fundamental frequency of the ATcut is limited to 40MHz for small diameter blanks.[52] Can be manufactured either as a conventional round disk, or as a strip resonator; the latter allows much smaller size. The thickness of the quartz blank is about (1.661mm)/(frequency in MHz), with the frequency somewhat shifted by further processing.[57] The third overtone is about 3times the fundamental frequency; the overtones are higher than the equivalent multiple of the fundamental frequency by about 25kHz per overtone. Crystals designed for operating in overtone modes have to be specially processed for plane parallelism and surface finish for the best performance at a given overtone frequency.[49]SC500kHz 200MHzthickness shear3515, 2154A special cut (Stress Compensated) developed in 1974, is a double-rotated cut (3515 and 2154) for oven-stabilized oscillators with low phase noise and good aging characteristics. Less sensitive to mechanical stresses. Has faster warm-up speed, higher Q, better close-in phase noise, less sensitivity to spatial orientation against the vector of gravity, and less sensitivity to vibrations.[58] Its frequency constant is 1.797MHzmm. Coupled modes are worse than the ATcut, resistance tends to be higher; much more care is required to convert between overtones. Operates at the same frequencies as the ATcut. The frequency-temperature curve is a third order downward parabola with inflection point at 95C and much lower temperature sensitivity than the AT cut. Suitable for OCXOs in e.g. space and GPS systems. Less available than ATcut, more difficult to manufacture; the order-of-magnitude improvement of parameters is traded for an order of magnitude tighter crystal orientation tolerances.[59] Aging characteristics are 2~3times better than of the ATcuts. Less sensitive to drive levels. Far fewer activity dips. Less sensitive to plate geometry. Requires an oven, does not operate well at ambient temperatures as the frequency rapidly falls off at lower temperatures. Has several times lower motional capacitance than the corresponding ATcut, reducing the possibility to adjust the crystal frequency by attached capacitor; this restricts usage in conventional TCXO and VCXO devices, and other applications where the frequency of the crystal has to be adjustable.[60][58] The temperature coefficients for the fundamental frequency is different than for its third overtone; when the crystal is driven to operate on both frequencies simultaneously, the resulting beat frequency can be used for temperature sensing in e.g. microcomputer-compensated crystal oscillators. Sensitive to electric fields. Sensitive to air damping, to obtain optimum Q it has to be packaged in vacuum.[45] Temperature coefficient for bmode is 25 ppm/C , for dual mode 80 to over 100 ppm/C .[61]BT500kHz 200MHzthickness shear (bmode, fast quasi-shear)498, 0A special cut, similar to ATcut, except the plate is cut at 49 from the zaxis. Operates in thickness shear mode, in bmode (fast quasi-shear). It has well known and repeatable characteristics.[62] Has frequency constant 2.536 MHzmm. Has poorer temperature characteristics than the ATcut. Due to the higher frequency constant, can be used for crystals with higher frequencies than the ATcut, up to over 50 MHz .[52]ITthickness shearA special cut, a double-rotated cut with improved characteristics for oven-stabilized oscillators. Operates in thickness shear mode. The frequency-temperature curve is a third order downward parabola with inflection point at 78 C . Rarely used. Has similar performance and properties to the SCcut, more suitable for higher temperatures.FCthickness shearA special cut, a double-rotated cut with improved characteristics for oven-stabilized oscillators. Operates in thickness shear mode. The frequency-temperature curve is a third order downward parabola with inflection point at 52 C . Rarely used. Employed in oven-controlled oscillators; the oven can be set to lower temperature than for the AT / IT / SCcuts, to the beginning of the flat part of the temperature-frequency curve (which is also broader than of the other cuts); when the ambient temperature reaches this region, the oven switches off and the crystal operates at the ambient temperature, while maintaining reasonable accuracy. This cut therefore combines the power saving feature of allowing relatively low oven temperature with reasonable stability at higher ambient temperatures.[63]AKthickness sheara double rotated cut with better temperature-frequency characteristics than AT and BTcuts and with higher tolerance to crystallographic orientation than the AT, BT, and SCcuts (calculated to be a factor 50 against a standard ATcut). It operates in thickness-shear mode.[59]CT300 900kHzface shear38, 0The frequency-temperature curve is a downward parabola.DT75 800kHzface shear52, 0Similar to CTcut. The frequency-temperature curve is a downward parabola. The temperature coefficient is lower than the CTcut; where the frequency range permits, DT is preferred over CT.[52]SLface-shear57, 0GT100kHz 3MHzwidth-extensional517Its temperature coefficient between 25 ... +75C is near-zero, due to cancelling effect between two modes.[52]E, 5X50 250kHzlongitudinalHas reasonably low temperature coefficient, widely used for low-frequency crystal filters.[52]MT40 200kHzlongitudinalET6630FT57NT8 130kHzlength-width flexure (bending)XY, tuning fork3 85kHzlength-width flexureThe dominant low-frequency crystal, as it is smaller than other low-frequency cuts, less expensive, has low impedance and low C0/ C1 ratio. The chief application is the 32.768kHz RTCcrystal. Its second overtone is about six times the fundamental frequency.[49]H8 130kHzlength-width flexureUsed extensively for wideband filters. The temperature coefficient is linear.J1 12kHzlength-thickness flexureJ cut is made of two quartz plates bonded together, selected to produce out of phase motion for a given electrical field.RTA double rotated cut.SBTCA double rotated cut.TSA double rotated cut.X30A double rotated cut.LCthickness shear11.17 / 9.39A double rotated cut ("linear coefficient") with a linear temperature-frequency response; can be used as a sensor in crystal thermometers.[64] Temperature coefficient is 35.4 ppm/C .[61]AC31Temperature-sensitive, can be used as a sensor. Single mode with steep frequency-temperature characteristics.[65] Temperature coefficient is 20 ppm/C .[61]BC60Temperature-sensitive.[65]NLSCTemperature-sensitive.[65] Temperature coefficient is about 14 ppm/C .[61]YTemperature-sensitive, can be used as a sensor. Single mode with steep frequency-temperature characteristics.[65] The plane of the plate is perpendicular to the yaxis of the crystal.[66] Also called parallel or 30-degree. Temperature coefficient is about 90 ppm/C .[61]XUsed in one of the first crystal oscillators in 1921 by W.G. Cady, and as a 50kHz oscillator in the first crystal clock by Horton and Marrison in 1927.[67] The plane of the plate is perpendicular to the xaxis of the crystal. Also called perpendicular, normal, Curie, zero-angle, or ultrasonic.[68]The letter T in the cut name marks a temperature-compensated cut a cut oriented in a way that the temperature coefficients of the lattice are minimal; the FC and SCcuts are also temperature-compensated.The high frequency cuts are mounted by their edges, usually on springs; the stiffness of the spring has to be optimal, as if it is too stiff, mechanical shocks could be transferred to the crystal and cause it to break, and too little stiffness may allow the crystal to collide with the inside of the package when subjected to a mechanical shock, and break. Strip resonators, usually ATcuts, are smaller and therefore less sensitive to mechanical shocks. At the same frequency and overtone, the strip has less pullability, higher resistance, and higher temperature coefficient.[69]The low frequency cuts are mounted at the nodes where they are virtually motionless; thin wires are attached at such points on each side between the crystal and the leads. The large mass of the crystal suspended on the thin wires makes the assembly sensitive to mechanical shocks and vibrations.[52]The crystals are usually mounted in hermetically sealed glass or metal cases, filled with a dry and inert atmosphere, usually vacuum, nitrogen, or helium. Plastic housings can be used as well, but those are not hermetic and another secondary sealing has to be built around the crystal.Several resonator configurations are possible, in addition to the classical way of directly attaching leads to the crystal. E.g. the BVA resonator (Botier Vieillissement Amlior, Enclosure with Improved Aging),[70][unreliable source?] developed in 1976; the parts that influence the vibrations are machined from a single crystal (which reduces the mounting stress), and the electrodes are deposited not on the resonator itself but on the inner sides of two condenser discs made of adjacent slices of the quartz from the same bar, forming a three-layer sandwich with no stress between the electrodes and the vibrating element. The gap between the electrodes and the resonator act as two small series capacitors, making the crystal less sensitive to circuit influences.[71][unreliable source?] The architecture eliminates the effects of the surface contacts between the electrodes, the constraints in the mounting connections, and the issues related to ion migration from the electrodes into the lattice of the vibrating element.[72] The resulting configuration is rugged, resistant to shock and vibration, resistant to acceleration and ionizing radiation, and has improved aging characteristics. ATcut is usually used, though SCcut variants exist as well. BVA resonators are often used in spacecraft applications.[73]In the 1930s to 1950s, it was fairly common for people to adjust the frequency of the crystals by manual grinding. The crystals were ground using a fine abrasive slurry, or even a toothpaste, to increase their frequency. A slight decrease by 12kHz when the crystal was overground was possible by marking the crystal face with a pencil lead, at the cost of a lowered Q.[74]The frequency of the crystal is slightly adjustable ("pullable") by modifying the attached capacitances. A varactor, a diode with capacitance depending on applied voltage, is often used in voltage-controlled crystal oscillators, VCXO. The crystal cuts are usually AT or rarely SC, and operate in fundamental mode; the amount of available frequency deviation is inversely proportional to the square of the overtone number, so a third overtone has only one-ninth of the pullability of the fundamental mode. SCcuts, while more stable, are significantly less pullable.[75]On electrical schematic diagrams, crystals are designated with the class letter Y (Y1, Y2, etc.). Oscillators, whether they are crystal oscillators or others, are designated with the class letter G (G1, G2, etc.).[76][77] Crystals may also be designated on a schematic with X or XTAL (a phonetic abbreviation, comparable to using Xmas for Christmas), or a crystal oscillator with XO.Crystal oscillator types and their abbreviations:ATCXO Analog temperature controlled crystal oscillatorCDXO Calibrated dual crystal oscillatorDTCXO Digital temperature compensated crystal oscillatorEMXO Evacuated miniature crystal oscillatorGPSDO Global positioning system disciplined oscillatorMCXO Microcomputer-compensated crystal oscillatorOCVCXO oven-controlled voltage-controlled crystal oscillatorOCXO Oven-controlled crystal oscillatorRbXO Rubidium crystal oscillators (RbXO), a crystal oscillator (can be an MCXO) synchronized with a built-in rubidium standard which is run only occasionally to save powerTCVCXO Temperature-compensated voltage-controlled crystal oscillatorTCXO Temperature-compensated crystal oscillatorTMXO Tactical miniature crystal oscillator[67]TSXO Temperature-sensing crystal oscillator, an adaptation of the TCXOVCTCXO Voltage-controlled temperature-compensated crystal oscillatorVCXO Voltage-controlled crystal oscillatorClock generatorClock drift Clock drift measurements of crystal oscillators can be used to build random number generators.Crystal filterErhard Kietz, who worked on electronic tuning forks and with quartz crystals for precise signal frequenciesIssac Koga inventor of the temperature-stable R1 Koga cutPierce oscillatorThin-film thickness monitorVariable-frequency oscillator (VFO)

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