Crystal, Silicon, Ceramic, and LC Material Properties and Features

A comparison of crystal oscillators and Si-MEMS oscillators

Preface

A wide variety of electronic devices require reference signals. Crystal devices are one source of reference clocks, but by no means are they the only one. Other sources include, LC oscillators, which consist of an inductor (L) and a capacitor (C) that resonate when connected to generate a frequency. CR oscillators, are used to charging/discharging circuits comprised of a capacitor (C) and resistor (R) to generate a reference frequency, and ceramic oscillators use piezoelectric ceramics consisting primarily of lead zirconium titanate (PZT); and silicon-based oscillators, which use micro-electromechanical systems (MEMS) technology. The type of oscillator you choose will depend on the application.
Ceramic oscillators are often used as the source for microprocessor clock signals and other low-frequency applications where frequency accuracy is noncritical. Ceramic oscillator frequencies range between 200 kHz and 100 MHz. Their frequency deviation at room temperature are typically around 0.1%-0.5%.

These oscillators have a price advantage, but the tradeoff of a ceramic oscillator is large frequency fluctuations in response to temperature changes, where the total frequency stability is low (about ±1.1%).
Crystal oscillators are largely used for applications where high frequencies and high frequency accuracy are required, such as wireless communications equipment. In recent years silicon-based oscillators (Si-MEMS oscillators) have shown performance gains, but there is still a fundamental performance gap among the various implementations. This white paper discusses the feature of crystal units and resonators made using various materials.

1. Comparison of crystal units and resonators

Crystal units and resonators used in oscillators that generate reference clocks come in a variety of types. A piezoelectrically actuated type, for example, uses the phenomenon of reverse piezoelectricity, where a voltage applied to a piezoelectric crystal produces a mechanical stress. An electrostatically actuated type, meanwhile uses electrostatic produced under the application of a high voltage. In all cases, however, their properties depend largely on the properties of the crystal (material).

Epson offers a variety of quartz crystal-based electronic products but, as mentioned in the preface, crystal units and resonators can be made from a variety of materials. Their general characteristics are summarized in Table 1 and explained further below.

Table 1: Comparison of crystal unit / resonator properties according to material

Crystal Unit / Resonator Material	Initial Frequency Deviation	Frequency/Temperature Coefficient	Q Value
Quartz(Crystal)	Excellent	Excellent	Excellent
Si	Poor	Poor	Good
Ceramic	Fair	Fair	Fair
LC, CR	Poor	Poor	Poor

1-1. LC & CR resonators

LC resonator circuits, consist of an inductor (L) and a capacitor (C). They are good for applications that require relatively high frequencies and a wide frequency tuning range. However, they are neither very accurate nor stable.
In addition, inductance has to be increased for low frequencies in order to meet resonance conditions, and they are ill-suited to miniaturization because they require a large coil. When miniaturization is required, a CR resonator which does not use an Inductor, can be used. The drawback of CR resonators is that it is hard to squeeze high frequencies out of them.

1-2. Ceramic resonators

Ceramic resonators use a piezoelectric element made primarily of PZT hardened at high temperature. They offer better accuracy than LC oscillators, but they also have a large initial frequency deviation (about ±0.5%). Therefore, they are widely used for low frequency applications in which frequency accuracy is not critical.

The temperature characteristics of ceramic resonators can be adjusted by changing the composition of the ceramic material, enabling these resonators to be flexibly adapted. On the other hand, since slight error in material composition and manufacturing variations can cause properties to vary, it is extremely difficult to ensure reproducibility.

The most outstanding characteristic of ceramic resonators is their fast rise time. Rise time affects elements of oscillation circuits, but, generally speaking, higher frequencies, lower load capacitances, and lower resonator Q values tend to result in faster oscillation. As indicated in Table 1, the Q value of ceramic resonators is lower than that of quartz and Si resonators, so ceramics have the edge when it comes to rise time. Given these characteristics, ceramic resonators are widely used in applications where accuracy is not all that critical but mainly when the speed of rise time is important.

1-3. Silicon resonators

Si resonators use single-crystal silicon, Q value which material has is better than ceramic’s, but is worse than crystal’s. In addition, Si resonators can be made inexpensively and in very small sizes when processed in batches on wafers using a semiconductor fabrication process. However, this type of convenient, high-throughput production makes adjustment on the individual resonator level difficult, and variations in the fabrication process are directly reflected in initial frequency deviation. Therefore, the frequency accuracy of individual resonators is compensated to some extent by compensating circuits.

The temperature/frequency characteristic (coefficient) of a single-crystal silicon exhibits first-order linearity of -20 to -30 ppm/°C, a large amount of change in response to temperature changes. When Si resonators are used, they are provided as temperature-compensated Si-MEMS oscillators that have a certain level of accuracy.

1-4. Quartz crystal units

Lastly, since quartz crystal units are based on a silicon-dioxide (SiO_2) material, they have a high Q value thanks to their high crystallinity and outstanding impedance characteristics. Furthermore, the quartz used is an anisotropic crystal and, depending on the way it is cut, produces temperature characteristics that have a cubic curve with an inflection point near room temperature and stable characteristics across a wide temperature range.

Since frequency is adjusted in the manufacturing process, the initial frequency deviation is also very small (on the order of several ppm). Thus, these crystal units are widely used in applications that require high accuracy, such as wireless communications equipment. When seen as standalone resonators, crystal units have extremely high accuracy.

As we have seen, the properties of the various materials from which crystal units and resonators are made deserve careful consideration when choosing the best product for the application. In the next section, we will explain the differences between oscillators that use silicon resonators (Si-MEMS oscillators) and oscillators that use quartz crystal units.

2. Comparison of the temperature characteristics of crystal units and silicon resonators

Let's consider in a little more detail the temperature/frequency characteristics mentioned earlier. The temperature characteristics of quartz and silicon are shown in Figure 1. Quartz crystals (here, AT-cut crystal units) exhibit stable characteristics over a wide temperature range and have an inflection point near room temperature. What these results indicate is that stable accuracy can be maintained in situations where temperature changes radically, even without adjustments, so quartz crystal can accommodate a wide range of applications.

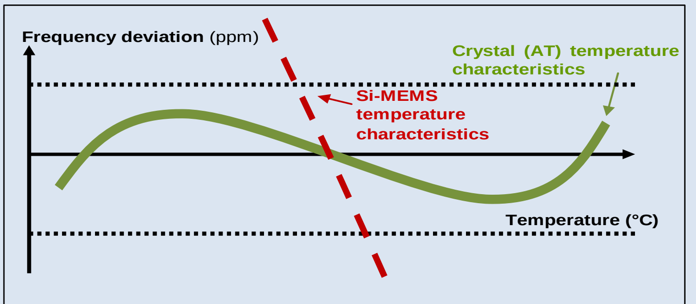

Figure 1. Si-MEMS & Crystal (AT) temperature characteristics

In contrast, silicon resonator temperature characteristics exhibit first-order linearity of -20 to -30 ppm/°C. When an oscillator is constructed using a resonator with these characteristics, the natural temperature characteristics of the crystal have to be compensated. Since crystal units are individually tuned to the desired frequency, initial deviation also shows a ppm-order width of variation.

However, silicon resonators, which are batch-processed on wafers to achieve maximum throughput, exhibit a large variation in the width of initial deviation unless they are individually tuned, a time-consuming process. For the foregoing reasons, Si-MEMS resonators are designed to be used as oscillators with compensation circuits and may have the potential for larger loads (power consumption) on the circuit side than quartz crystals. Therefore, there is a significant difference in characteristics in these as crystal units and resonators.
The difference in performance in oscillators used on the actual market is shown in the next section.

3. Characteristics of crystal oscillators and Si-MEMS oscillators

Reference signal requirements vary significantly, depending on the application, but in general, oscillators are chosen based on parameters such as initial frequency deviation of oscillation, frequency/temperature stability, and noise and jitter characteristics. Si-MEMS oscillators compensate the temperature characteristics of their silicon resonators with peripheral circuits to achieve stability.

The peripheral circuits used for compensation are called "fractional-N PLL circuits" (or "Frac-N PLLs" for short). A Frac-N PLL is a phase-locked loop circuit that uses a fractional divider to generate an output frequency that is a multiple of the input frequency. The frequency demultiplier at each temperature point of the silicon resonator is changed using this method to control the oscillation frequency of the output signal and perform temperature compensation. An example of temperature compensation using this method is shown in Figure 2.

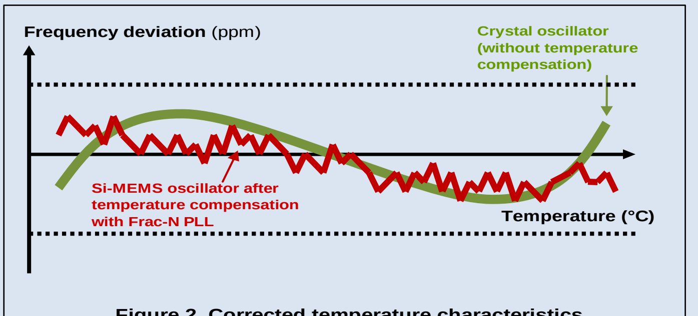

Figure 2. Corrected temperature characteristics

The characteristic shown in brown in Figure 2 is the characteristic after temperature compensation has been applied by Frac-N PLL.

As previously mentioned, the temperature characteristic of a silicon resonator exhibits first-order linearity, so compensating itself can be executed based on a simple compensation formula, but because the amount of change is so large compared to the temperature characteristic of a crystal unit, analog temperature compensation is not possible. Therefore, the used temperature domain is divided into smaller zones and careful compensation with a digital circuit such as a Frac-N PLL is applied while changing the frequency demultiplier in each zone. However, discontinuous frequency jumps such as those shown in Figure 2 occur when the demultiplication ratio is switched. This causes the phase of output signals to change at discontinuous temperature points of the oscillation frequency, leading to degradation of noise and jitter characteristics. When silicon resonators are used in wireless equipment that communicates based on phase modulation technology, correct modulation/demodulation is not possible in the presence of noise, potentially preventing the accurate transmission and reception of data.

Oscillators based on crystal units can be used over a wide temperature range even without temperature compensation (frequency tuning). Moreover, since they do not use PLLs for temperature compensation (only the natural oscillation frequency is used even in products where the demultiplication ratio is changed by a PLL circuit), crystal oscillators can maintain the smooth native temperature characteristics of the crystal across a range of temperatures (a state in which there are no discontinuous jumps in frequency).

As a result, there is no degradation of noise and jitter characteristics, and the potential for problems to occur in wireless equipment is extremely low.

Of course, it is possible to alter the design of the silicon resonators themselves (e.g., control dimensions or change electrode materials), individually apply temperature compensation, and change the demultiplication ratio for only the initial value, but this ends up diluting the advantages that Si-MEMS enjoyed in the first place, such as high throughput and low cost.

Finally, the demand for crystal units and resonators from the communications equipment industry has been accelerating in recent years.

Given this trend, the need for crystal units that provide stable characteristics even without tuning is likely to rise further. When users select electronic components, they need to adequately understand the characteristics of materials so that they can choose the best component for their application. Epson will continue to expand and enhance its lineup of reliable crystal devices to meet these needs.