INFICON

TECHNICAL NOTE

The Technology of The Intelligent Oscillator for Quartz Crystal Measurement and Its Advantages for Thin Film Processes

Quartz crystals have been used to measure the deposition rate and thickness of thermally evaporated and sputtered thin films for optics and electronics for over 30 years[1,2]. During that time, improvements in the understanding of the basic transducer physics, the engineering of the transducer, and the measurement of small time intervals have made measurements more accurate and enhanced the compatibility of the transducer with the harsh vacuum evaporation environment. Also improvements in oscillator circuitry and crystal design have gradually increased crystal life. All of these improvements come together in the INFICON ModeLock[3] measurement methodology. This technology provides superior thickness repeatability, rate control, and crystal reliability.

This article looks first at the evolution of the "active oscillator" quartz crystal measurement technology, starting with simple frequency measurement and progressing to period measurement and a Z-match technique. Then it examines how ModeLock replaces and overcomes the limitations of the active oscillator.

THE EVOLUTION OF QUARTZ CRYSTAL MEASUREMENT TECHNOLOGY

All quartz crystal deposition monitors use the high mass sensitivity of a quartz crystal's resonant frequency to measure and control the deposition rate and final thickness of a vacuum deposition. A voltage applied across the faces of a piezoelectric crystal distorts the crystal in proportion to the applied voltage. If the crystal is properly shaped, sharp electromechanical resonances occur at certain discrete frequencies of the applied voltage, corresponding to a particular standing acoustic wave condition in the crystal. Adding mass to the face of a resonating quartz crystal decreases the frequency of these resonances.

This mass-induced change in the crystal's resonant frequency is repeatable and has been quantified for specific oscillating modes of quartz. The monitor crystal's resonant frequency can be measured by using an oscillator circuit's frequency as a reference. The frequency-determining element of the oscillator circuit depends on another resonant crystal. When the deposited material's density is known, the deposited thickness on the monitor crystal can be inferred from its frequency shift. Less than an atomic layer of an added material can be detected easily.

THE ACTIVE OSCILLATOR

The first measurement technique used in quartz crystal deposition monitors was a simple measurement of frequency. Knowledge of the quantitative relationship between the mass of the deposited material and the frequency shift allowed the determination of the amount of material being deposited on a substrate in a vacuum system, a measurement that was neither convenient nor practical prior to this understanding.

Although instruments using the frequency measurement technique were useful, they had a limited range of accuracy, typically maintaining accuracy only for frequency shifts less than 0.02 times F_q, the base frequency of the quartz.

In 1971, the period measurement technique, which measured the period of the signal from the crystal rather than the frequency, was put into practice. The period measurement technique used a reference oscillator not affected by the deposition. The reference oscillator was of a much higher frequency than the monitor crystal to obtain the fine time measurement precision necessary to resolve the small, mass-induced frequency shifts associated with rapid measurements, low deposition rates, and low density materials. For example, the measurement precision is especially critical in the production of optical filters or very thin layered superlattices grown at low rates. In many cases, the desired properties of these films can be lost if the layer-to-layer reproducibility exceeds more than one or two percent.

The next innovation was based on the work of Miller and Bolef[4] and Lu and Lewis[5]. Miller and Bolef rigorously treated the resonating quartz and deposited film system as a one-dimensional continuous acoustic resonator. Lu and Lewis developed the simplifying Z-match[6] equation, with Z being the acoustic impedance ratio.

Introduction of the microprocessor made it possible to solve the Z-match equation quickly enough for process control. The user only needed to enter the Z-ratio for the film being deposited. The Z-match equation has been tested and found to hold for a number of materials[7]. It has been proven valid for frequency shifts as high as 0.4 times F_q, the base frequency of the quartz—a significant improvement over both the frequency measurement technique (valid to 0.02 times F_q) and the period measurement technique (valid to 0.05 times F_q).

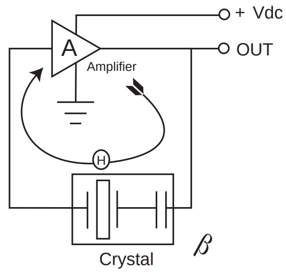

Figure 1

All of these measurement techniques (frequency, period, and Z-match) rely on an active oscillator circuit, as shown in Figure 1. This feedback circuit actively resonates at a frequency determined by the electromechanical characteristics of the crystal. Oscillation is sustained as long as the amplifiers provide sufficient gain to offset losses in the crystal and as long as the circuit and the crystal together can provide the necessary phase shift.

The crystal resonator is roughly equivalent to a sharply tuned LCR circuit, as shown in Figure 2. At resonance the impedance is minimized and equal to R, and the quality factor, Q, is maximized. The quality factor, a ratio of the energy stored to the energy dissipated per cycle, can easily exceed 100,000 for properly shaped quartz.

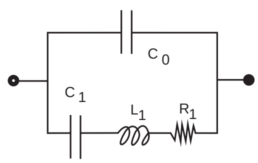

Figure 2

The crystal oscillator's stability is derived from the rapid change of phase for a small change in the crystal's frequency near the series resonance point, as shown in Figure 3. Oscillator circuits are normally designed so that the crystal is required to produce a phase shift of zero degrees, forcing the circuit to operate at the crystal's series resonance frequency.

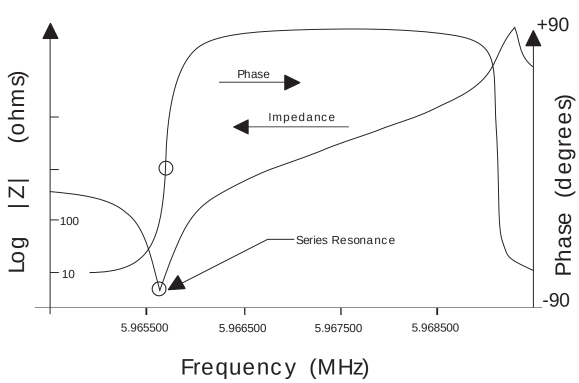

Figure 3

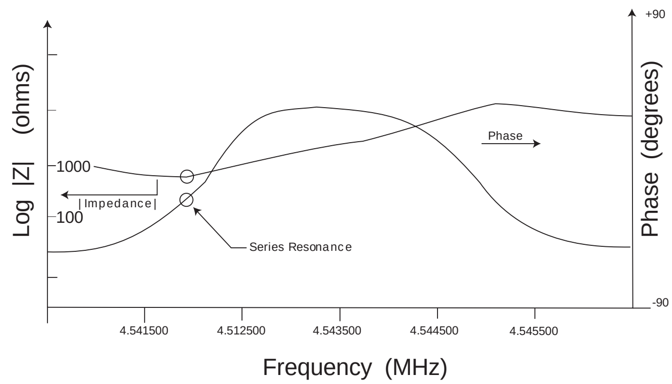

Figure 4

A crystal's electrical characteristics change with added mass, as shown in Figure 4, which is characteristic of a heavily loaded crystal. Because the crystal has lost the steep phase slope typical of a new crystal, any noise in the oscillator circuit translates into greater frequency jitter than would be evident with a new crystal. In the extreme, the basic phase/frequency shape is lost, and the crystal is not able to provide the full ±90 degrees of phase shift that it could when it was new.

As the crystal is coated, the impedance at series resonance increases, indicating a loss of crystal Q. When this occurs, the circuit may occasionally resonate at one of the anharmonic frequencies. The oscillator may continue to oscillate at the anharmonic, or it may alternate between the fundamental and anharmonic modes, a condition known as mode hopping. In addition to causing noise in the rate signal, mode hopping can also lead to false termination of the film because of the apparent thickness change associated with the shift from one resonant

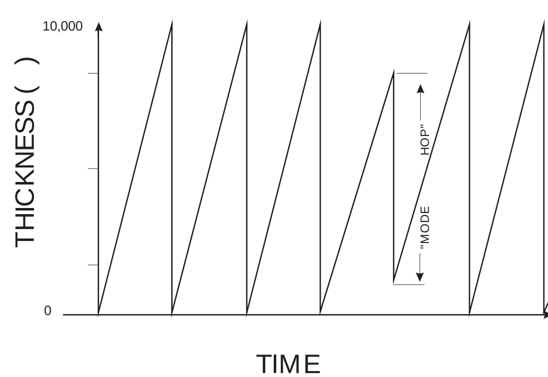

Figure 5

frequency to another. The monitor often continues to operate under these conditions since there is no outward evidence of mode hopping except for a discontinuity in the film thickness, as is shown in Figure 5. Although the apparent thickness changes dramatically, the mass sensitivity, and therefore the true rate, changes only by about five percent.

THE CRYSTAL'S SERIES RESISTANCE OR "ACTIVITY"

The greater the crystal's response to the applied voltage, the more likely it is that the crystal will continue to oscillate as material is added. This quality is sometimes called activity or complex impedance, but the effect is more properly related to the series resistance. Higher series resistance means that less current is accepted and returned from the crystal. Since the physical motion of the crystal is current-driven, low current levels produce little piezoelectric motion. A new 6 MHz monitor crystal will typically have less than 10 or 20 ohms of series resistance at the fundamental mode. A conventional oscillator circuit will continue to operate well until the series resistance of the crystal exceeds approximately 200 ohms. For well-behaved materials, such as copper, this resistance is not normally exceeded, even for a frequency shift in excess of 1 MHz. Although these oscillators will continue to resonate with a crystal that has a high resistance, they are often unable to initiate the oscillation of a high-resistance crystal after a disconnection or power failure.

In practice, the series resistance is not a strict predictor of continued operation. Because of low mobility, some materials do not deposit as continuous films on the crystal surface but take on an amorphous, granular texture, through which the acoustic wave is unable to propagate continuously. In these cases, the crystal can be used for only very thin layers. The series resistance is not initially affected, but, when it does increase, it does so unexpectedly and precipitously.

Film stress can also affect crystal life. Stress can bend the crystal and induce a frequency change not related to mass, or it can cause the electrode to tear from the quartz. Stress can cause a quick and unpredictable failure during deposition or even destroy a crystal during system venting. If the electrode is strongly adhered to the quartz, the combination of rapid temperature change and moisture adsorption increases stress until the quartz itself fractures.

MODELOCK: A FREQUENCY-SYNTHESIZED, PHASE-SENSITIVE, INTELLIGENT OSCILLATOR

In 1990, INFICON introduced a new technology that replaces the active oscillator and overcomes the active oscillator's limitations. This measurement system, ModeLock, constantly tests the crystal's response to an applied frequency. It not only determines the resonant frequency but also verifies that the crystal is oscillating in the desired mode. ModeLock is essentially immune to mode hopping and thus is not subject to the thickness and rate inaccuracies of active oscillators. It is fast and accurate, determining the crystal's frequency with precision better than 0.0055 Hz at a rate of 10 times per second.

This new intelligent measurement system uses the phase/ frequency properties of the quartz crystal to determine the resonant frequency. As shown in Figure 6, it applies a synthesized sine wave of a specific frequency to the crystal and measures the phase difference between the applied signal voltage and the current passing through the crystal. When a crystal operates at series resonance, this phase difference is exactly zero degrees; the crystal behaves as if it were pure resistance. The reactances of the inductive and capacitive branches cancel each other.

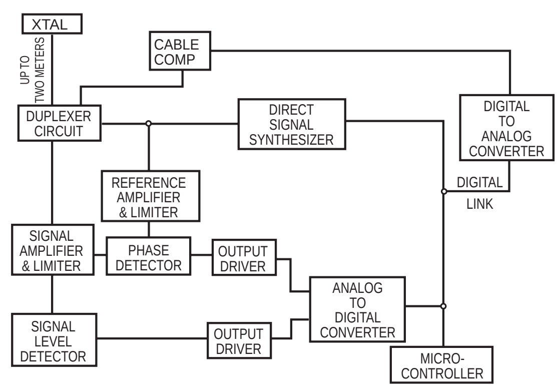

Figure 6

By separating the applied voltage and the current returned from the crystal and by monitoring the output of a phase comparator, ModeLock determines whether the applied frequency is higher or lower than the crystal's resonant frequency. At frequencies well below any resonance, the crystal's impedance is capacitive. In terms of phase angle, the current leads the voltage. At frequencies slightly higher than resonance, a crystal's impedance is inductive in nature. This is valuable information if the resonance frequencies can be applied to the crystal, with a change in sign of the phase comparator marking the resonance events. For AT-cut crystals, the type used in ModeLock instruments, the lowest frequency event encountered is the fundamental. The events slightly higher in frequency are anharmonics.

This information is beneficial not only for initialization, but also for the rare instances when the instrument loses track of the fundamental.

Once the resonance spectrum of the crystal is determined, the instrument tracks the changing frequencies and periodically provides frequency measurements for subsequent conversion to thickness. Rather than sweep the applied frequency over the entire range of possible frequencies for each measurement, a more efficient strategy based on a phase-change algorithm precisely determines the resonant frequency. The algorithm adjusts the applied frequency according to phase change information and allows a "lock" on the resonant frequency. A direct digital synthesizer, or DDS, closely coupled to a dedicated microprocessor and related circuitry, makes this process possible at unprecedented speed and frequency accuracy—and at a practical cost. All the necessary actions—comparing the phase, digitizing the phase difference, comparing that value to the desired value, deciding to increase or decrease the applied frequency, then generating the new frequency—can take place 150,000 times per second.

The result is that ModeLock offers significant advantages over active oscillators: immunity from mode hopping, increased speed of measurement, improved precision of measurement, and extended crystal life in many applications. The technique also allows for the automatic determination of the acoustic impedance parameter, the Z-ratio, a feature that is impossible with the active-oscillator approach. The patented* Auto-Z technique is discussed in detail in the literature[8].

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[8]A. Wajid, Rev. Sci. Instrum. 62(8), 2026 (1991).

*U.S. Patent #5,112,642.

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