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MASTER

RADIATION-INDUCED FREQUENCY TRANSIENTS IN

AT, BT AND SC CUT QUARTZ RESONATORS*

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Abstract

Earlier studies of transient frequency changes in high-purity swept AT quartz resonators led to the conclusion that impurity induced effects were, if present, small, while the observed changes were qualitatively and quantitatively well characterized in terms of the time changing temperature of the vibrating quartz and its effect on frequency.

In the present work we have prepared 5 MHz, AT cut fifth overtone, and BT and SC cut third overtone resonators from a single stone of Sawyer swept Premium-Q quartz. The resonators were operated in precision ovenized oscillators at or near their turnover temperatures. Pulsed irradiation, at dose levels of the order of 10^6 rads (Si) per pulse, was accomplished at the Sandia Labs' Hermes II facility operating in the Braggstrahlung mode.

The experimental data display negative frequency transients for the AT cut resonators, positive frequency transients for the BT cut resonators, and very small transient effects for the SC cut resonators. From these experimental results we conclude that 1) no measurable impurity-induced frequency changes (elastic modulus changes) are being observed in this high purity swept quartz and that 2) the frequency transients are accurately modeled in terms of transient temperature effects stemming from the thermal characteristics of the resonator structure.

Introduction

In earlier work^{1,2} on transient frequency changes in high-purity swept AT cut quartz resonators, we were led to the conclusion that impurity induced effects were, if present, small. The observed changes were qualitatively and quantitatively well characterized in terms of the time changing temperature of the vibrating quartz and its effect on frequency. Thermal transient induced frequency changes in AT cut resonators were observed as early as 1959³ and described empirically as a function of the time changing

ambient.⁴ Holland's⁵ work on thermal gradient effects in thickness shear resonators led to the TFC cut, which is approximately equivalent to Eeriksson's stress compensated, SC, cut.⁶ Holland's calculations deal with thermal gradients in the thickness direction while, in the present work, the thermal modeling of the resonator structure is concerned with radial heat flow and relates the instantaneous frequency change linearly to the rate of change of temperature at the oscillating boundary.

Some insight into the mechanism responsible for this effect has been offered by Warner.⁷ He has shown that parallel field excitation reduces the thermal shock sensitivities associated with changing ambient, and he attributes this reduced sensitivity to the absence of quartz-electrode stresses. This attribution is consistent with the observation of a lack of frequency change in SC cut resonators exposed to time changing temperatures.⁸

For further investigation of these ideas relative to our radiation studies, it was suggested that measurements on BT and SC cut resonators could offer additional clarification of the induced thermal effects as well as offering an enhanced sensitivity to frequency changes stemming from impurities. The TFC cut, or SC cut, is designed to minimize thermal shock-induced frequency shifts and should thus allow sensitive measurements of impurity effects (elastic modulus changes) on the resonator frequency, although this notion is dependent upon how the various frequency determining elastic moduli are individually modified by the radiation. The BT cut, on the other hand, has a thermal shock coefficient opposite in sign to the AT cut and one should see positive frequency transients resulting from radiation heating. From an impurity effects perspective, however, King's⁹ measurements, as well as earlier experiments by Frenkel,¹⁰ showed that in natural quartz BT cut resonators, the radiation-induced steady-state frequency changes were as great as 10^5 times the changes observed in AT cut resonators and of the same sign. If the radiation-induced transient frequency changes followed this steady-state frequency-change behavior, therefore, one should see large negative frequency excursions after pulse irradiation.

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Experimental Details

In the present work we have prepared 5 Mhz, AT cut fifth overtone, and BT and SC cut third overtone resonators* from a single stone of Sawyer[†] swept Praxair quartz. Except for the quartz blank thickness and the electrode thickness, all the resonator construction details are the same. The resonators were operated in precision oscillators at or near their turnover temperatures in proportionally-controlled double ovens. Pulsed irradiation was accomplished at the Sandia Labs' Hermes II facility which is a 10 Mev, 70 ns pulse width, electron beam source operating in the Bremsstrahlung mode.

Electrical noise and EMP effects were avoided by doubly shielding the oscillator, oven, and signal cables. Although lead collimators were used to minimize exposure to the oscillator and oven control circuitry, some evidence for radiation-induced changes in the oscillator transistor has been seen and will be discussed below. These experimental details and the basic instrumentation shown in Figure 1 have been described before but are mentioned here for easier reference.

Frequency was recorded at 0.1 second intervals from approximately 5 seconds before the radiation pulse to several hundred seconds after with a resolution of approximately 2 parts in 10^9 . At dose levels of the order of 10^4 rads (Si) per pulse, prompt photoconductivity in the oscillator caused momentary (approximately 30 microseconds) shutdown. Temporary oven turn-off also resulted from the significant temperature rise in the oven assembly. The oven heating current as well as the AGC level, which is a measure of resonator resistance, was also monitored.

Experimental Results and Modelling

The AGC measurements showed no resistance changes resulting from the radiation. Resistance-dependent frequency changes were therefore not present.

The physical structure of the resonator pertinent to heating considerations is shown in Figure 2 and was used to construct a thermal model of the resonator. The equivalent electrical circuit of the lumped-element thermal model is shown in Figure 3. For purposes of calculating dynamic and static frequency changes stemming from radiation-induced temperature changes, the various nodes in the model are instantaneously charged to voltage levels equivalent to the nodal radiation doses. The details of such modelling efforts have been presented earlier^{1,2} and, for calculations of frequency changes, the voltage and time rate of change of voltage have their equivalent in temperature and time rate of change of temperature. In particular, at the quartz vibrational zone, C_0 in Figure 3, the electrical state translates to the instantaneous frequency via equation 2 in Reference 1, repeated here

$$\Delta f/f(t) = \rho \frac{\Delta T(t)}{\Delta T} + \gamma(T(t) - T(0))$$

*Fabricated by Frequency Electronics Inc., New Hyde Park, NY

[†]Sawyer Research Products, Inc., Enslin, OH

The frequency at time t is not only the static function of temperature γ , but depends also on thermal transients, $\rho \frac{\Delta T}{\Delta T}$ (see Reference 4). The coefficient, ρ , in the transient frequency term has been measured for the AT, BT, and SC cut resonators.³ However, if the empirical dependence has its basis in a thickness-direction thermal gradient in an electrodeless resonator, then an acceptable theoretical treatment should demonstrate the relationship between heat flow, occurring either radially or conceivably via a thermal path through the electrodes to the oscillating region, and such a thermal gradient. Warner's⁷ results with parallel field excited resonators could be interpreted in this perspective also, although it is not clear whether a thickness-direction temperature gradient or a quartz-electrode interface stress is the mechanism responsible for the frequency change.

Computer calculations of thermal equilibration, after pulsed radiation deposition, generate the frequency transient curves shown in Figures 4, 5 and 6. The experimental data for the AT resonators of this study are shown in Figure 4 and display the same qualitative and quantitative behavior observed in earlier studies of high-purity, swept-quartz resonators. The correlation with the thermal model suggests very little impurity-induced frequency effects in this high-purity quartz. It should be mentioned, however, that differences in sweeping techniques can produce variations in radiation-induced resonator frequency changes¹¹ and therefore further qualification of quartz material and purification processes is usually necessary to demonstrate radiation hardness.

Early time structure in the frequency transient is associated with heat flow into the oscillating region from the ribbon supports, while later time structure is associated with cooling followed by oven-controlled heat flow.

The experimental data for the BT and SC cut resonators are shown in Figures 5 and 6. The unstructured transient for the SC resonator in Figure 5 showed a permanent, approximately 2-3 pp 10^4 , negative frequency offset which was recovered by replacing the oscillator transistor. Subsequent exposure to the radiation pulse again produced the unstructured negative frequency offset. Moreover, the negative frequency transients observed with AT cut resonators have tended to mask this effect. Further experimentation is planned for studying these radiation effects on oscillator transistors.

The raw data for the BT resonator frequency changes also displayed evidence of such a transistor produced offset and, therefore, the BT data shown in Figure 5 have been displaced positively by 3 pp 10^4 . The excellent agreement, both qualitative and quantitative, with the thermally-induced changes calculated from the model, again suggests a predominance of radiation heating effects over impurity-generated frequency changes. No calculations were made for the SC resonator since neither static nor dynamic temperature changes should produce a frequency change detectable on the scale shown.

In Figure 6 we display the frequency transient results from irradiation when operating the SC cut resonator at 16 degrees below turnover. The thermal calculations were performed with a zero-value thermal-transient coefficient and the data have again been translated positively by 2.4 pp 10^4 . The agreement between

the data as generated in this experiment as well as in the experiment at turnover and the thermal modelling calculations, further supports a description of the induced frequency transients based on radiation heating of the resonator.

Conclusions

Further evidence has been established confirming the conclusion that high-purity swept-quartz, as represented in this study by SARP Swept Promium-Q material, is sufficiently pure that thermal frequency effects dominate under pulsed irradiation. Transient frequency changes induced in BT, SC and AT cut resonators can be accurately described by thermal modelling of the resonator structure which takes into account both static and dynamic temperature effects arising from radiation heating. The stress compensated SC cut, or thermal transient compensated TTC cut, fabricated from high-purity quartz, furthermore, offers an excellent radiation-resistant resonator, since both radiation-induced impurity effects and radiation-induced thermal effects on frequency are minimized.

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Figure Captions

Figure

- 1 Block diagram of data recording system for measuring oscillator frequency and equivalent crystal resistance as a function of time following a short-duration radiation exposure.
- 2 Structure of crystal resonator and oven assembly.
- 3 Lumped-element thermal-model of resonator and oven structure in equivalent electrical form.
- 4 Frequency transient following pulse irradiation for AT cut resonators.
- 5 Frequency transient following pulse irradiation for BT and SC cut resonators.
- 6 Frequency transient following pulse irradiation for SC cut resonator operated below turnover.

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