TEMPERATURE SENSORS BASED ON $GaPO_4$

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Abstract - Results of investigations of temperature sensors using singly rotated Gallium Orthophosphate ($GaPO_4$) Y-cut resonators are presented in this paper.

Depending on rotating angle the most important parameters - sensitivity, resolution and linearity - differ in a wide range. Theoretical calculations leads to cuts owning nearly a linear response with sensitivity between 44.5 ppm/°C and 46.5 ppm/°C within a temperature range from room temperature to 600 °C with a high resolution of about 10^{-6} °C. First measurements confirm the theoretically predicted sensitivity.

The broad thermal stability range of $GaPO_4$ can also be used for temperature sensors based on surface acoustic wave devices. By theoretical calculations, suitable orientations with high temperature coefficients are identified.

I. INTRODUCTION

The high temperature stability of the α-quartz like phase of $GaPO_4$ up to 970 °C favours this crystal for sensors used in high temperature environments. An interesting application is a resonant piezoelectric temperature sensor based on bulk acoustic waves (BAW) with a large measuring range of more than 1000 °C, from low temperatures up to 970 °C [1].

Temperature sensors made of quartz can be used up to about 350 °C because of the beginning of the stress induced twinning at this temperature which decreases stability and sensitivity of the sensor. At a temperature of 573 °C the α-β phase transition occurs and piezoelectricity disappears, so quartz cannot be used at higher temperatures. There are several resonant piezoelectric temperature sensors based on quartz with different properties. A successful development was the LC (linear temperature coefficient)-cut from Hewlett-Packard [2] with an accuracy of 0.02 °C and a useable resolution of 10^{-4} °C. In the era of microprocessors non-linearity of resonant frequency versus temperature became less important and so in 1987 Ziegler developed the so called HT-cut quartz temperature sensor [3], a singly rotated Y-cut ($\Theta = -4$ °) with a high sensitivity of 90 ppm/°C.

All of them have the small useable measurement range in common.

II. THEORETICAL CALCULATIONS

The calculations are based on the theory by Stevens and Tiersten for doubly rotated quartz trapped energy and contoured resonators [4]. First calculations were done for singly rotated thickness shear Y-cut resonators in the temperature range from room temperature to 600 °C.

The best cut for crystal thermometers has to achieve the following specifications:

- the change in resonant frequency in measurement range should be high
- the resonant frequency temperature dependence has to be unique
- the electromechanical coupling should be high.

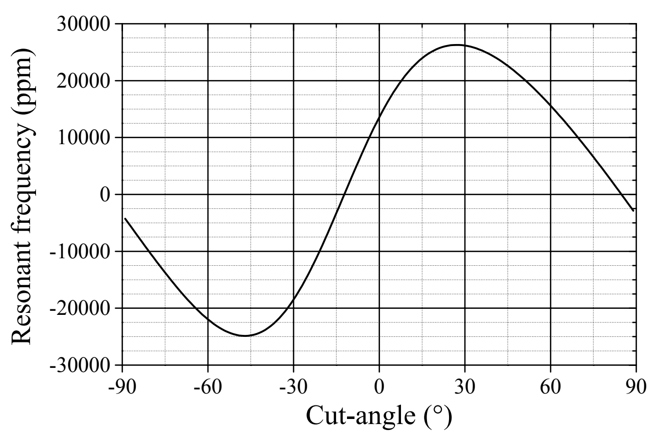

Figure 1: Change in resonant frequency between 25 °C and 600 °C depending on cut-angle

Relating to these requirements some calculations were made. Figure 1 shows the change in resonant frequency depending on cut-angle Θ (cut-angle Θ according to standard IEEE 176-1978).

Two cuts show nearly the same change in resonant frequency over the whole measurement range, the cuts near Y+27° and Y-47°, respectively. A restrictive condition is the resonant frequency versus temperature dependence, which has to be unique in the whole temperature range for this application. The characteristics are shown in Figure 2, where the cut near Y-27° has a positive temperature coefficient of frequency (TCF) and the cut near Y-47° has a negative TCF.

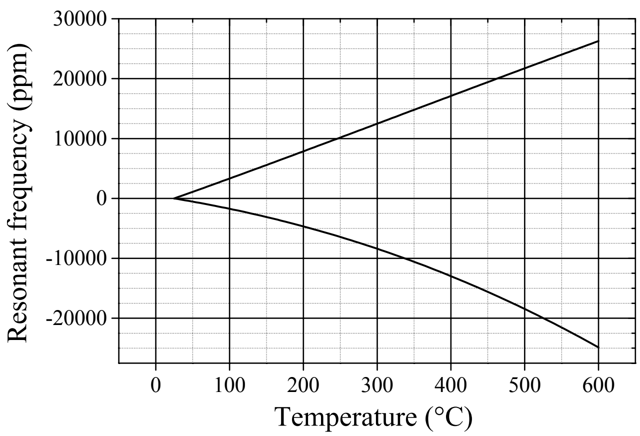

Figure 2: Resonant frequency versus temperature

The different sensitivities of these two cuts are shown in Figure 3.

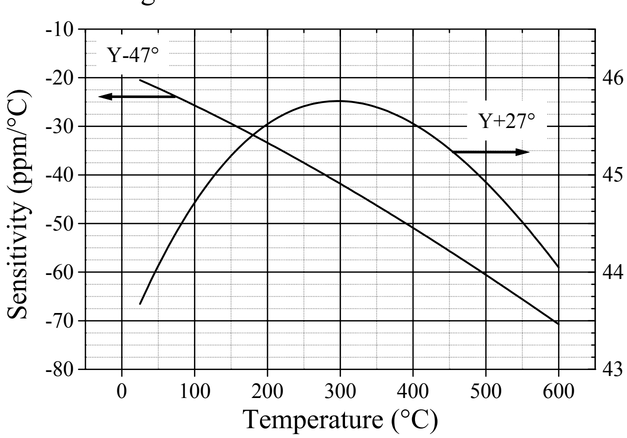

Figure 3: Sensitivity of the cuts Y+27° and Y-47°

An important parameter is the electromechanical coupling which describes the interaction between electrical and mechanical forces. The higher the coupling the smaller the electrodes can be and the unharmonic modes are more suppressed also. The electromechanical coupling coefficients *k* of these two cuts are shown in Table 1.

Table 1: Electromechanical coupling *k*

Resonator	*k* (%)
Y+27°	16.9
Y-47°	3.6

These calculations lead to the decision that the cut near Y+27° is the most promising cut for temperature sensors basing on BAW-resonators.

Table 2: Properties between 25 °C and 600 °C

Resonator	Resonant frequency change (ppm)	Sensitivity (ppm/°C)
Y+27.16°	26581	≈ 45
Y-46.93°	-25131	-20 ÷ -70

III. Temperature Sensor Preparation and Measurement Setup

The resonators are circular discs with a diameter of 5 mm and a resonant frequency of about 6 MHz. They are plano-convex lapped with a radius of curvature of 50 mm. The electrodes are sputtered Pt-layers with a thickness of 200 nm and a diameter of 2.5 mm. The crystals are mounted in a standard HC-52/U holder, where the crystallographic X-axes of the crystal is perpendicular to the bonding surfaces of the holder to reduce the damping of the crystal due to holder mounting. The crystal is electrically contacted to the holder with a high temperature stable electroconductive glue (Aremco Pyro-duct 597). Figure 4 shows the geometry of the crystals with electrodes.

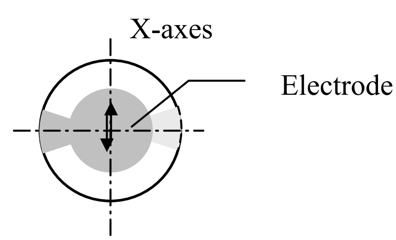

Figure 4: Crystal with electrodes

Before mounting into the holder the crystals were tempered for 8 hours at a temperature of 700 °C. This was done to make a pre-ageing to increase the stability of the sensor and reduce ageing effects.

The temperature dependence was measured in a dry-well calibrator in the temperature range up to 140 °C and in the temperature range up to 600 °C in a tubular heater.

Measurement Setup

To ensure an equal temperature at the resonator and the temperature sensor a small steel body as heat-reservoir with holes for both sensors was used, shown in Figure 5. This steel body is connected with two rods to a connection plate with connectors for the oscillator and the resistance meter.

The characteristic properties are measured with the passive method with a HP 4195a network analyzer.

The measurements in the temperature chamber are done in the active method with an oscillator which provides the resonant frequency and a damping signal too. The resistance of the Pt100 was measured in 4-wire technique.

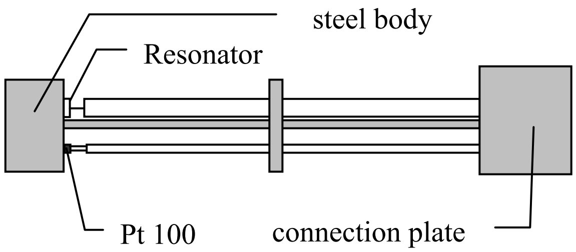

Figure 5: Measurement arrangement

IV. EXPERIMENTAL RESULTS

In Figure 6 the temperature resonant frequency characteristic is given. Four cycles are shown in this Figure, i. e. the resonator was heated up from 60 °C to 600 °C with a following cooling down back to 60 °C for four times.

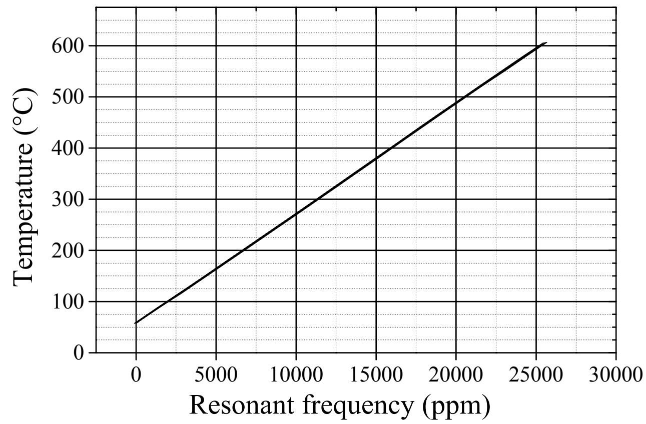

Figure 6: Temperature – resonant frequency characteristic

A better illustration of the behaviour is to show the deviation to an idealised curve. In Figure 7 the deviation to a fitted curve (3. order polynomial fit) of the first heating up from first cycle is shown. The numbers are indicating the consecutive measurement cycles.

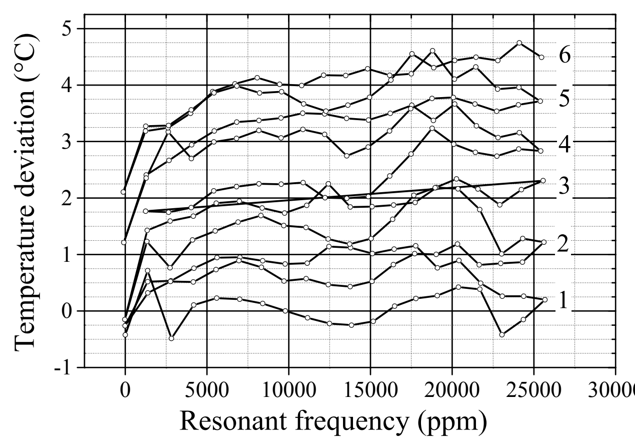

Figure 7: Temperature deviation of consecutive measurement cycles

The measured temperature sensitivity of the sensor is shown in Figure 8. The derived sensitivity of all 6 measurement cycles are shown. The dashed line indicates a 2. order polynomial fit.

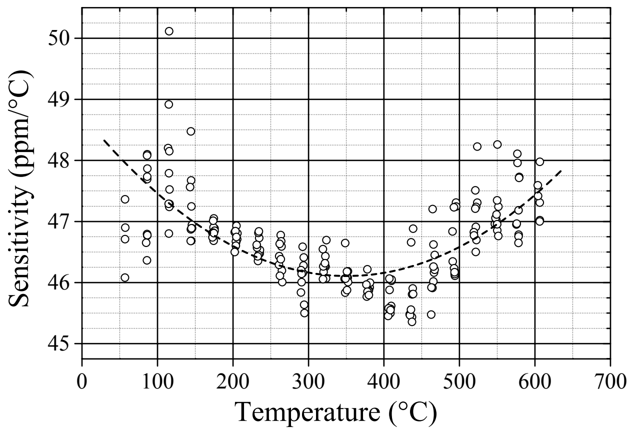

Figure 8: Sensitivity of the resonator between 25 °C and 600 °C

V. SAW Calculations

Theoretical calculations lead to the resonant frequency - temperature dependence shown in Figure 9. The cut is a Y-Boule -5° (or Y-Boule +5° cut, which leads to the same results) with an expected sensitivity between 15 ppm/°C at 25 °C and 4.5 ppm/°C at 700 °C.

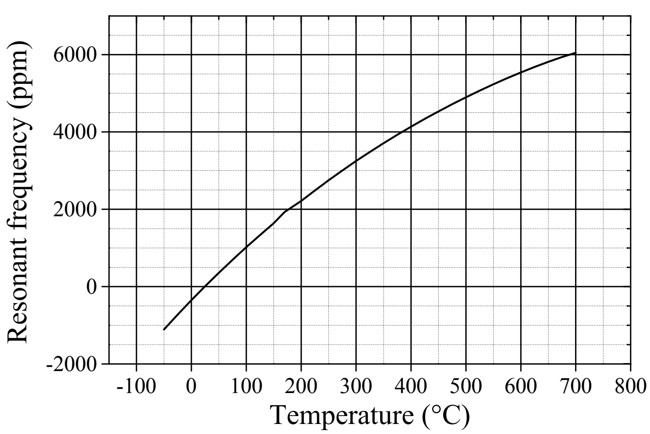

Figure 9: Theoretically calculated resonant frequency temperature dependence of a SAW Y-Boule -5° resonator

VI. Discussion and Conclusion

First investigations show the potential of $GaPO_4$ BAW resonators for temperature sensors up to 600 °C.

The predicted sensitivity of about 45 ppm/°C is reached.

The measurements were done in air in a tubular heater. The reached stability of the resonators is too high to determine different parameters in this environment accurately. So the next step has to be to make these experiments with encapsulated and hermetically sealed crystals in a highly stable temperature chamber to determine the stability (ageing), resonant frequency - temperature behaviour and hysteresis accurately.

By theoretical calculations, suitable orientations of SAW devices with high temperature coefficients are identified. Passive remote monitoring of the surface acoustic wave frequency or delay time allows wireless temperature sensing at temperatures where no electronic circuits can be operated.

VII. References

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[4] D. S. Stevens and H. F. Tiersten, “An analysis of doubly rotated quartz resonators utilizing essentially thickness modes with transverse variation,” J. Acoust. Soc. Am., vol. 79 (6), pp. 1811-1826, June 1986.