TEMPERATURE COMPENSATED $GaPO_4$ RESONATORS WITH Q FACTORS HIGHER THAN 10 MILLION AT 6 MHZ

F. Krispel, H. Thanner, P. W. Krempl, C. Reiter, P. M. Worsch and W. Wallnöfer

AVL List GmbH, Physics Research, Hans List Platz 1, 8020 Graz, Austria;

Corresponding author: Email: ferdinand.krispel@avl.com

ABSTRACT

Thickness shear resonators (6 MHz, fundamental mode) made of gallium orthophosphate ($GaPO_4$) crystals with a cut angle near Y-84° and a very low coupling have shown very high Q factors [2], thus it is called HiQ cut. The properties of some new HiQ resonators are investigated by a passive (HP network analyzer) and an active (oscillator) measurement method. The motional resistances of HiQ resonators are several kΩ at normal pressure conditions but decrease to several hundreds of Ω under vacuum conditions.

Q factors between 5 and 6 million are obtained at a pressure of about 0.07 mbar with the active method and up to 13 million at 0.04 mbar with the passive method. Since high Q factors promise low phase noise, further investigations are focussed on the short time stability.

Keywords: Quality factor, $GaPO_4$, gallium phosphate, Q factor, HiQ resonator, BAW

1. INTRODUCTION

$GaPO_4$ [1] is called the high tech brother of quartz because of its promising physical properties. The doubled piezoelectric coefficient compared to quartz leads to a higher electromechanical coupling coefficient of $GaPO_4$ resonators at room temperature. Resonators with high coupling (15 % – 16 %) and turnover temperature at 25 °C have Q factors up to 300000. The Q factor rised up to 1.2 million at low pressure (0.04 mbar).

Oven controlled crystal oscillators (OCXO) need a low motional capacitance C_1. This leads to a cut in the vicinity of the Z cut. The Z cut shows no piezoelectricity and no coupling. For a good temperature stability of the series resonant frequency the turnover point of the parabolic frequency temperature behaviour was chosen at 85 °C. Figure 1 shows the coupling coefficient k depending on the angle θ, which means a rotation of a Y cut across the x-axes to the Z cut, calculated with the material constants of $GaPO_4$ [1].

The designed and tempered (annealed) resonators with low coupling show a high motional resistance R_1, as expected, but under vacuum conditions the motional resistance drops dramatically. Thus first experiments with thickness shear resonators (6 MHz, fundamental mode) made of gallium orthophosphate crystals with a cut angle near Y-84° (HiQ cut) have shown very high Q factors up to 13 million, which depend on the residual gas pressure [2].

The properties of some HiQ cut $GaPO_4$ resonators are investigated by the following two measurement methods:

By the passive method, using a network analyzer, different resonators are compared. The best unloaded Q factors have been obtained at low pressures by $GaPO_4$ resonators with a coupling near 0.25 % under vacuum conditions. The active method uses a special designed oscillator circuit for resonators with high motional resistances, automatic level control and a possibility for cable compensation. A phase shifter in the loop allows a slight variation of the phase of the loop to get the change of the resonant frequency depending on this variation.

$$k^2 = \frac{e_{eff}^2}{\varepsilon_{eff}\, c_{eff}^D} \quad \text{with} \quad e_{eff} = d_{eff}\, c_{eff} \qquad (1)$$

Where c mean the elastic constants, d the piezoelectric constants, e the piezoelectric modulus and ε the dielectric coefficients. All constants depending on the rotation angle θ and temperature are effective combinations of the tensor components.

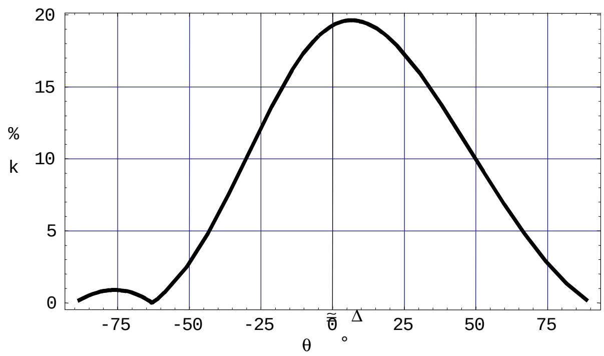

Figure 1: Coupling of rotated Y+θ cut $GaPO_4$ resonators at 85 °C

2. BACKGROUND

A piezoelectric resonator can be represented by a simple series resonant circuit bypassed with a static capacitance C_0 (Figure 2). The losses are comprised in the motional resistance R_1. C_1 is the motional capacitance and L_1 the motional inductance. Electrodes, enclosure and cable are included in the static capacitance C_0.

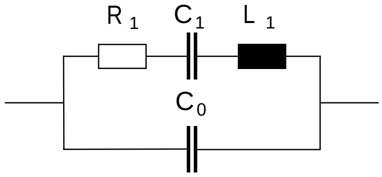

Figure 2: Simple crystal equivalent circuit

The series resonance frequency f_s can be calculated with equation (2) but because of the parallel capacitance C_0 the minimum impedance of the resonator is not at the same frequency as the phase vanishes.

$$f_s = \frac{1}{2\pi\sqrt{L_1 C_1}} \qquad (2)$$

The quality factor (Q factor) of the resonator is defined in (3):

$$Q = \frac{\omega_s L_1}{R_1} = \frac{1}{\omega_s C_1 R_1} \qquad (3)$$

where $\omega_S = 2\ \pi\ f_S$. In the vicinity of the resonance frequency relation (4) holds:

$$\left.\frac{d\varphi}{df}\right|_{fs} = \frac{f_S}{2Q_B} \qquad (4)$$

Q_B means the effective Q factor where external losses, for example seen by the electronic sustaining circuit (oscillator), are included in the form of $R_{eff} = R_1 + R_{ext}$, φ is phase in radiant.

If the damping constant $\tau_1 = R_1 C_1$ is introduced then τ_1 is composed of the different damping mechanism [3].

$$\tau_1 = \tau_\alpha + \tau_\phi + \tau_G + \tau_E \qquad (5)$$

τ_α...acoustic losses in the material
τ_ϕ...losses due to plate geometry
τ_G...damping because of the surrounding gas
τ_E...electrical resistance of the electrodes

The last term is very small in most cases. The second loss τ_ϕ can be made negligible by an adequate size of the resonator with a good energy trapping. If the enclosure is evacuated then the third term diminishes and the crystal's acoustic loss can be measured.
This leads for the material quartz to the relation (6):

$$Q \cdot f \approx 16 \cdot 10^{12} \qquad (6)$$

This is called the frequency quality product, and it is constant if the resonators are well designed. The best Q factors for the material quartz have been obtained with 5 MHz resonators, which are driven at the 3^{rd} or 5^{th} overtone [3].

3. PREPARATION

HiQ resonators were sawn with a diamond blade, lapped and polished. One side was contoured by manual convex lapping and polishing. The raw design was for all resonators the same ($GaPO_4$). Quartz resonators with a low coupling were also investigated for comparison. The cut Y-71° of quartz yielded roughly the same coupling coefficient as the HiQ cut.

- Cut: Y-84° (HiQ) for $GaPO_4$ samples
- Cut: Y-71° for quartz samples
- Diameter: 7.4 mm
- Thickness: see Table 1 and 2, second column
- Radius of convex curvature: R = 100 mm
- Surface polished
- Electrodes: 20 nm NiCr, 180 nm Au

Figure 3 shows a picture of the resonator after the sputter process and its mounting in a big metal block. The background shows the vacuum chamber. This system was also used to measure the frequency temperature characteristics of the HiQ resonators.

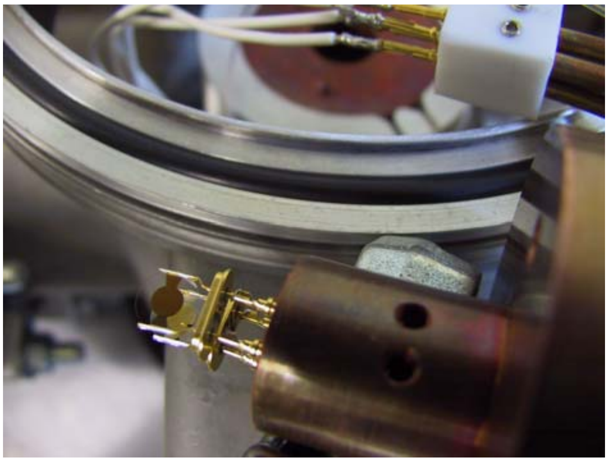

Figure 3: Two HiQ resonators mounted with HC-49/U holder and the vacuum chamber in the background

The properties of the resonators are summarized in Table 1 and 2. In the second column of both tables, the thickness of the samples is shown. In the last process the resonators (with sputtered electrodes) were exposed to a temperature of 320 °C for 15 hours (quartz samples 350 °C for 11 hours).

Table 1: Overview of HiQ resonators made of $GaPO_4$, not tempered, under atmospheric pressure

Nr	D	f_s	f_p	k	R_1	C_1	Q
	[mm]	[Hz]	[Hz]	[%]	[Ω]	[aF]	[10^3]
1	0.271	5872280	5872317	0.35	2587	28.4	369
2	0.163	9800249	9800292	0.24	2452	23.3	284
3	0.271	5903270	5903307	0.35	2599	27.4	379
4	0.271	5910948	5910988	0.35	3150	27.0	317
5	0.163	9815810	9815855	0.24	2359	23.9	288

Table 2: Quartz samples, cut: Y-71°, not tempered, under atmospheric pressure

Nr	D	f_s	f_p	k	R_1	C_1	Q
	[mm]	[Hz]	[Hz]	[%]	[Ω]	[aF]	[10^3]
10	0.271	7573993	7574031	0.25	6832	11.5	268
11	0.271	7572733	7572779	0.21	6886	8.0	382

4. EXPERIMENTAL

4.1 MEASUREMENTS WITH NETWORK ANALYZER

Passive measurements were made with the network analyzer HP 4195A. The calibration, which includes the compensation of the cable to the resonator, was done in the used region of frequency.

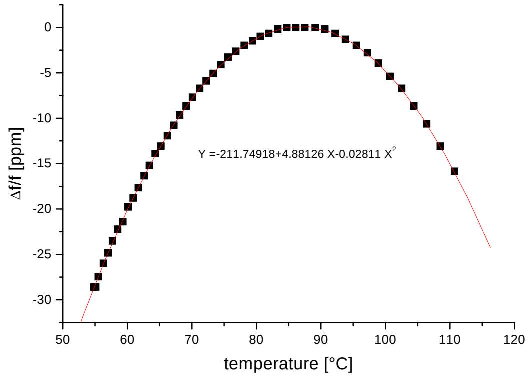

Figure 4: Frequency temperature characteristic of HiQ resonators made of $GaPO_4$

Two measurement methods were applied: First the equivalent circuit (Figure 2, Table 1 and 2) was calculated automatically and in the second method equation (4) was used to get the quality factor.

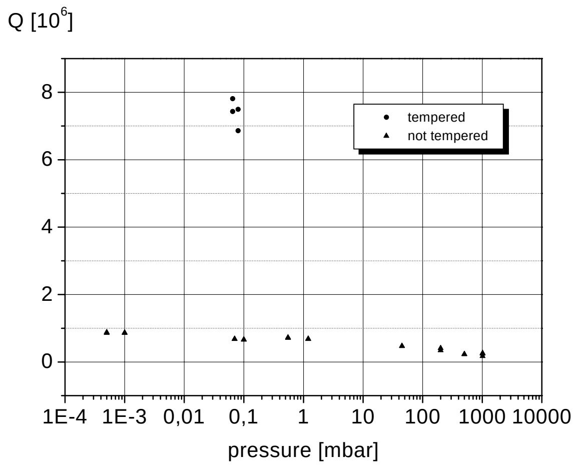

Figure 5: Influence of pressure on quality factor, determined with network analyzer and equation (4), of tempered and not tempered $GaPO_4$ resonators (Y-84 °) [1]

Figure 5 shows the dependence of the Q factor on pressure for tempered and not tempered HiQ resonators. The maximal Q factors achieved in vacuum are listed in Table 3 and 4 for HiQ and quartz resonators, respectively. Q* in Table 3 means that the Q factors are estimated after the second method using equation (4). $\Delta\varphi/\Delta f$ has been measured where the admittance is a maximum.

Table 3: Q factors of $GaPO_4$ resonators in vacuum (with and without tempering) determined by network analyzer using equation (4)

No	tempered	p [mbar]	Q* [-]
1	no	0.03	1 750 000
2	no	0.03	1 600 000
3	yes	0.04	13 000 000
4	yes	0.07	5 400 000
5	yes	0.05	8 700 000

Table 4: Q factors of quartz resonators in vacuum, determined by network analyzer using equivalent circuit evaluation

No	tempered	p [mbar]	Q [-]
10	no	0.045	500 000
11	no	0.033	775 000

The quartz samples no. 10 and no. 11, which had been tempered at 350 °C after these measurements, showed no piezoelectric response afterwards.

4.2 OSCILLATOR MEASUREMENTS

The HiQ resonators were also measured with an active method. Due to the relatively high motional resistance R_1, an oscillator designed for microbalance measurements was used to get the frequency and damping behaviour of the HiQ resonators. The block scheme is shown in Figure 6.

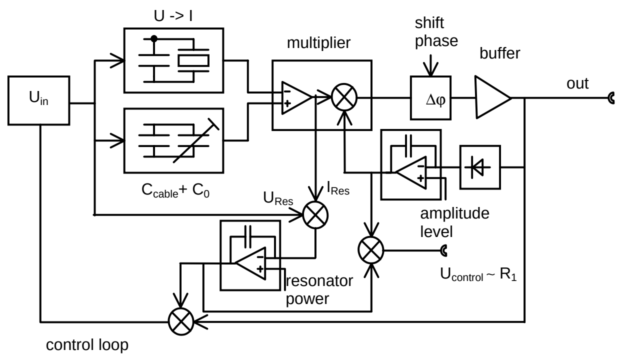

Figure 6: Oscillator schematic

It consists of a cable compensation, which is necessary because of the high motional resistance, an automatic level control and a phase shifter. The latter electronic part allows to apply a small change of phase in the oscillator loop which leads to a shift of frequency. These quantities are used to get the loaded Q factor of the HiQ resonators in an active loop.
For the active measurements the HiQ resonators were put inside a vacuum chamber (Figure 3) using a HC 49/U holder. A presupply pump produced a vacuum of 0.065 mbar. A control unit keeps the temperature of the sample at the turnover point (depending on resonator: 76 – 81 °C). The drive level dependence of the equivalent circuit was studied using resonator 3 and is shown in Table 5.

Table 5: R_1, Δf_s and Q_B (loaded Q) factor of resonator number 3 depending on drive level at 78 °C

P_R [µW]	R_1 [Ω]	Δf_s [Hz]	Q_B [10^6]
5.6	378	0	2.74
20	329	-1.00	4.56
27	357	-1.59	6.80
130	340	-8.3	1.10

P_R denotes the drive level, Δf_s is the change of the resonance frequency (5.903514 MHz at 78 °C). Q_B is the loaded Q estimated by equation (4). For the drive level measurement an active probe and an oscilloscope are used to measure the voltage across the resonator (U_{in}). The pressure dependence of the loaded Q factor and R_1 of resonator 3 at a drive level of 18 µW and 81.4 °C is shown in Figure 7. The product of loaded Q and R_1 is roughly constant (1.4 – 1.7·10^9 Ω).

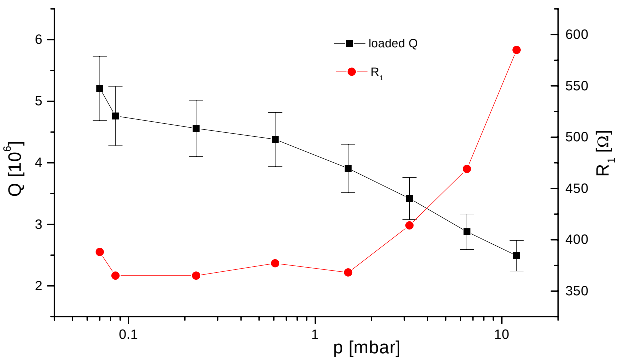

Figure 7: Dependence of Q_B and R_1 on pressure at 81.4 °C (resonator no. 3)

4.3 Comparison active – passive measurements

In Table 6 the results of the two measurement methods are compared. The motional resistance R_1 is very high at normal pressure so that the sustaining stage of conventional oscillators is too weak to start an oscillation. So only the low pressure measurements can be compared.

Table 6: Results of passive (p) and active (a) measurements of resonators 3 and 4

No.	T [°C]	p(Q_{max}) [mbar]	P_R [µW]	f_s [Hz]	Q_{max} [10^6]
3 p	25	0.040	88	5902911	13
a	78.1	0.065	27	5903514	6.8
4 p	25	0.070	36	5910660	5.4
a	78.1	0.065	10.7	5911303	1.8

The applied voltage is the same for both resonators but the motional resistance R_1 is different (881 Ω in resonator 4) which leads to differing drive levels. The differences in resonance frequencies can be explained by the different temperatures. The Q factor is significantly higher as measured by the passive method.

5. DISCUSSION

The two measurement methods do not deliver the same results. The much higher Q factor measured with the passive method cannot be explained with the lower pressure alone. A possible cause is the different drive level, which is possibly too high with the passive method. Because of the high Q factor the amplitudes of the resonators reach the nonlinear region and maybe an interfering resonance can be produced.
One significant feature is that only tempered resonators (made of $GaPO_4$) show a strong increase of the Q factor. One explanation is that most strains are softened during the high temperature. The same should be expected for quartz. But it seems that the tempering process at 350 °C for at least 10 hours of the used quartz cut leads to changes in the quartz samples, most propable twinning, avoiding any excitation of oscillation.

The frequency Q factor product is higher for $GaPO_4$ than for quartz:

$Q \cdot f = 77 – 85 \cdot 10^{12}$	$GaPO_4$, HiQ cut, passive, tempered
$Q \cdot f = 40 \cdot 10^{12}$	$GaPO_4$, HiQ cut, active, tempered
$Q \cdot f = 16 \cdot 10^{12}$	quartz, different cuts [3]
$Q \cdot f = 6 \cdot 10^{12}$	quartz, Y-71°, passive, not tempered

Further investigations are focussed on the short time stability. Measurements to obtain the Allan variance and the phase noise are in progress. Since possible applications for high stability time and frequency bases ask for very high Q factors and extremely low phase noise, this cut is a very promising candidate. Due to the possibility of high temperature pre-ageing, it is expected that the ageing is also low, so that oven controlled stand-alone devices may be obtained with excellent short and long term stability.

6. REFERENCES

[1] C. Reiter, P.W. Krempl, H. Thanner, W. Wallnöfer, P. Worsch, “Material properties of $GaPO_4$ and their relevance for applications“; 3rd European Workshop of Piezoelectric Materials, Montpellier, October 2000; Ann. Chim. Sci. Mat. 26 (2001) 91-94; see also: www.gapo4.com

[2] C. Reiter, H. Thanner, W. Wallnöfer, P.M. Worsch, P.W. Krempl; ”Elastic constants and temperature-compensated orientations of $GaPO_4$“; Proceedings of the 15th European Frequency and Time Forum; pp. 50-54; Neuchàtel; March 2001.

[3] B. Neubig, W. Briese, ”Das große Quarzkoch-buch” (in German), Feldkirchen: Franzis, 1997