Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 70 (2015) 1012 – 1016
Physics Procedia

2015 International Congress on Ultrasonics, 2015 ICU Metz

On the modeling of electrical response of SAW resonator-based sensors versus temperature

S. Ballandras[a] , T. Laroche[a], E. Courjon[a] , W. Daniau[b], T. Baron[b] ,J. Garcia[a]
and S. Alzuaga*

[a] *frec|n|sys SAS, 18 rue Alain Savary, 25000 Besançon, France*
[b] *FEMTO-ST, 15B Avenue des Montboucons, 25000 Besançon, France*
[c] *SENSeOR SAS, 18 rue Alain Savary, 25000 Besançon, France*

Abstract

Surface acoustic wave (SAW) resonators built on Langasite (LGS) are capable to withstand temperature in excess of 900◦ C and demonstration of wireless interrogation of packaged sensors up to 700◦ C has been achieved for several tens of hours. These promising results emphasize the need for an accurate characterization of the raw material in order to design SAW resonators with a high level of confidence in the prediction, particularly concerning the temperature coefficient of frequency (TCF). Several data set have been published for LGS, offering prediction capabilities but also a significant level of data dispersion. Therefore, the evaluation of the effective thermal properties of SAW under periodic gratings turns out less robust than expected. Based also on published data and on measurements achieved within the SAWHOT project, harmonic admittance calculations have been achieved for deriving the evolution of mixed matrix parameters allowing for accurate SAW device simulation at any temperature. Adjusting the temperature coefficients then yield improved sets of material coefficients for design purpose. Using these data, we have demonstrated the possibility to develop a differential temperature sensor operating at temperature up to 600°C.

Keywords:

---

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: author@institute.xxx

doi:10.1016/j.phpro.2015.08.211

1. Introduction

Surface acoustic wave (SAW) resonator-based sensors built on Langasite (LGS) have been developed to measure temperature up to 900°C and demonstration of wireless interrogation of packaged sensors up to 700°C for several tens of hours has been achieved. These promising results indicate the possibility for developing high temperature sensors for harsh environment purposes. They also emphasize the need for effective material coefficients allowing for designing SAW resonators with a high level of confidence in the prediction of the device electrical response and more of its temperature coefficient of frequency (TCF). Several data set have been published for LGS, yielding a wide range of prediction capabilities but also a significant level of data dispersion yielding more or less robust evaluation of the effective properties of Rayleigh waves under periodic metal gratings. The achievement of the SAWHOT project has yield numerous experimental results of SAW resonators on various LGS crystal cuts, yielding a consistent data base for a comparative evaluation of the SAW characteristics prediction quality provided by the above-mentioned set of LGS constants (elastic, piezoelectric, dielectric and thermal expansion fundamental coefficients as well as effective thermoelastic constants).

Previous works were dedicated to introduce thermoelastic properties of piezoelectric crystals in the analysis of infinite-periodic acoustic wave-guide using harmonic admittance approaches, yielding several advances in the understanding of actual device operation versus temperature. In the present work, the possibility to derive the thermal evolution of all the wave parameters used to design and optimize SAW devices is exploited to develop a simulation tool based on the mixed-matrix formalism. This tool is developed to provide a comprehensive representation of the temperature dependence of the electrical response of SAW devices. In that purpose, the temperature dependences of the wave velocity of course but also of the reflexion coefficient, directivity, conductance and capacitance are established using polynomial developments allowing to compute the wave parameters for any temperature. These parameters are used to simulate the device response at the corresponding temperature, accounting of course for the thermal expansion of the device along the propagation direction. The interest of this approach is illustrated for SAW devices on directive crystal cuts for which dramatic changes of the SAW parameters versus temperature may occur, such as the (YX*lt*)/48.5°/26.7° Langasite (LGS) cut. For this crystal orientation, theory/experiment assessment shows that the origin of the temperature-induced modifications of the device response is strongly related to directivity and reflection changes when increasing the temperature. In the pursuit of this work, a differential temperature sensor has been developed combining Rayleigh-wave resonators built on the above LGS cut and the (YX) cut. This sensor has been remotely interrogated when submitted to temperature in excess of 600°C, providing a reliable and accurate estimation of the environmental temperature. The paper describes the model approach and reports on the experimental assessment of the differential sensor. Further development are mentioned as a conclusion

2. Modeling approach

Electrical models of SAW devices are computed mainly along two approaches, namely the Couping-of-Mode (CoM) method and the P-matrix or mixed-matrix technique. In the later approach, each section of the device is represented by a cell with two acoustic ports and one electrical connection (for the transducer region only of course) represented by the potential V and the current I. The acoustic field is represented by scalar input E and output S displacements at each acoustical port. Scattering parameters (transmission and reflection coefficients) allows for the simulation of acoustic interaction within the cell whereas coupling coefficients describe electromechanical interaction between electrical and acoustic phenomena. As mixed matrix have been described in many references, only the principal matrix relations are reported here in (1):

$$\begin{Bmatrix} S_1 \\ S_2 \\ I \end{Bmatrix} = \begin{bmatrix} r_1 & t & \alpha_1 \\ t & r_2 & \alpha_2 \\ -\alpha_1 & -\alpha_2 & Y \end{bmatrix} \begin{Bmatrix} E_1 \\ E_2 \\ V \end{Bmatrix} \tag{1}$$

where *r* and *t* and the acoustical scattering parameters, α is the electromechanical coupling coefficient and *G* and *B* are the admittance parameters. All these parameters depend on the phase of the wave defined as:

$$\varphi = 2\pi f \frac{L}{V}\left(1 - j\frac{\chi}{40\log(e)}\right) \tag{2}$$

Note that in (2), the equivalent losses are represented by the parameter χ holding for viscoelastic and propagation (radiation) losses. The conductivity of the electrode is also taken into account, yielding supplementary loss mechanisms varying along temperature *T*. At first order, this phenomenon is represented as follows:

$$\sigma(T) = \sigma_0 (1 + CTR_1 (T - T_0)) \tag{3}$$

In fact all parameters can be developed along a polynomial expansion versus temperature. The corresponding polynomial expansion are reported hereafter:

$$V(T) = CTV_0 + CTV_1(T - T_0) + CTV_2(T - T_0)^2 + CTV_3(T - T_0)^3 \tag{4}$$

$$G(T) = CTG_0 + CTG_1(T - T_0) + CTG_2(T - T_0)^2 + CTG_3(T - T_0)^3 \tag{5}$$

$$\sin(\Delta)(T) = CTR_0 + CTR_1(T - T_0) + CTR_2(T - T_0)^2 + CTR_3(T - T_0)^3 \tag{6}$$

$$\delta_{per}(T) = \square\delta_{0\,per} + \delta_{1\,per}(T - T_0) + \delta_{2\,per}(T - T_0)^2 + \delta_{3\,per}(T - T_0)^3\square \tag{7}$$

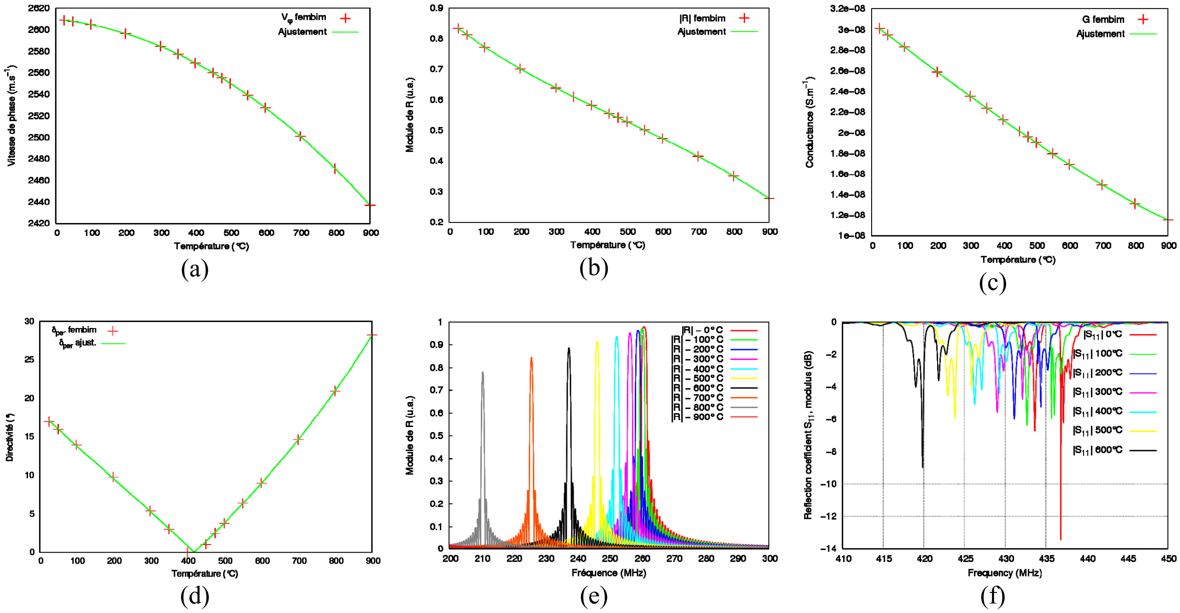
$$\varepsilon_{per}(T) = \varepsilon_{0\,per} + \varepsilon_{1\,per}(T - T_0) + \varepsilon_{2\,per}(T - T_0)^2 + \varepsilon_{3\,per}(T - T_0)^3 \tag{8}$$

$$\alpha_{loss}(T) = \alpha_{loss0} + \alpha_{loss\,1}(T - T_0) + \alpha_{loss2}(T - T_0)^2 + \alpha_{loss3}(T - T_0)^3 + \alpha_{loss4}(T - T_0)^4 \tag{9}$$

$$\sigma(T) = \sigma_0\left(1 + (CTR_1 - \alpha^{(1)})(T - T_0) + (CTR_2 + \alpha^{(1)2})(T - T_0)^2 + CTR_3(T - T_0)^3\right) \tag{10}$$

$$p(T) = p(T_0) \times \left(1 + \alpha_1^{(1)}(T - T_0) + \alpha_1^{(2)}(T - T_0)^2 + \alpha_1^{(3)}(T - T_0)^3\right) \tag{11}$$

Note that the expansion of the electrode along the normal of the plate has been neglected here, has yielding almost no changes on the relative electrode height for the usual electrode thicknesses. All the temperature coefficients of these developments but the thermal expansion and conductivity related parameters have been fitted from harmonic admittance computations. They have been then inserted in our mixed-matrix simulation tool, allowing for the derivation of the S_{11} response of the resonator on the whole thermal range (see Fig. 1f). A modification of Silvestrova set of material constants was used for theory/experiment agreement purpose.



(a) (b) (c)

(d) (e) (f)

Figure 1: Theoretical computation of the thermal dependence of Rayleigh waves propagation on (YXlt)/48.5°/26.7° LGS cut and its impact of resonator characteristics (a) phase velocity (b) conductance (c) reflection coefficient (d) directivity (e) 200-electrode Bragg mirror reflection (f) S_{11} parameter

1. Sensor implementation and test

Package and substrate materials require coefficients of thermal expansion as close as possible to avoid any additional stress on the LGS dice. The whole package is composed of a standard SMD ceramic case (7.1×9.1 mm^2), connected to the LGS dice by gold wire-boding (Fig.2). The case is connected to an alumina plate with patterned connection, the corresponding footprint being achieved with AgPb alloy to avoid solder migration. Stainless steel antennas and ceramic case are connected to the pattern using tin solder. An additional conditioning is required to preserve the device integrity when exposed to high temperature. The corresponding process is currently under patent application process and will be described when presented at the conference.

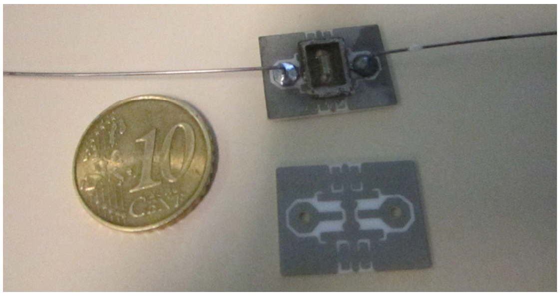
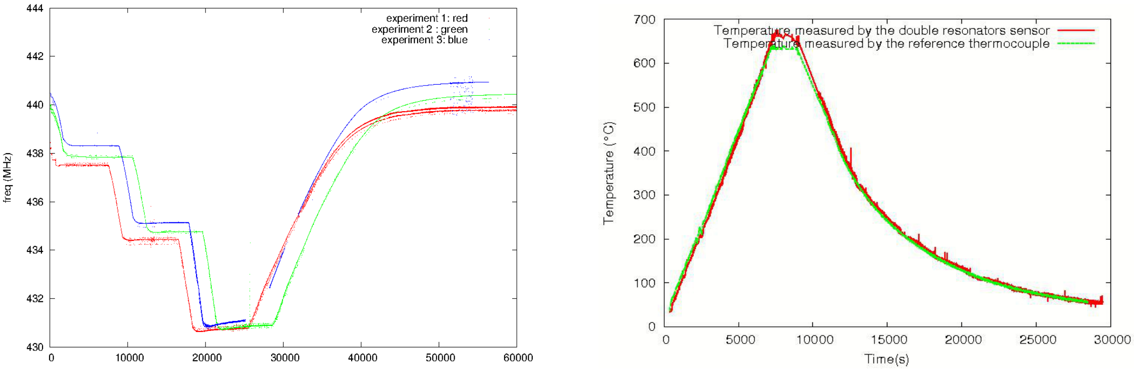


Fig. 2: Different stages of the packaging process (top: bonded SAW on alumina plate with antennas)

As explained above, LGS is used for temperature measurements above 500°C. As measurements are expected on the whole temperature range (25–700°C), a wide band version of SENSeOR's reader was used (440 MHz ± 10 MHz instead of classical 434MHz-ISM configuration). Several temperature cycles (25/300/500/700/25°C) are applied to the packaged LGS resonator. The later decreases by 300 kHz after each cycle, as shown in Fig. 3a, the frequency is only shifted at intermediate temperature (room, 300 and 500°C). The evolution of the frequency at 700°C after each process is less significant (50 kHz). Operation defects were observed after various cycle numbers (2 to 5) depending on the samples. Failure analysis shows various origins of defects (such as connection failures or IDT destruction) but globally the devices were found to operate at 700°C for duration ranging from 10 to 40 hours. Finally, we have combined (YX*lt*)/48.5°/26.7° and (YX)-cut based resonators for the development of a differential temperature sensor, remotely interrogated at temperature up to 600°C, providing a very reliable temperature measurement when compared to a usual wired resistive thermo-probe (Fig. 3b).



(a) (b)

Fig. 3: Wireless interrogation of LGS-based SAW resonators near the 434 MHz-centred band (a) single resonator tested from room temperature to 700°C (b) remotely-controlled differential sensor, comparison with a thermocouple measurement

2. **Conclusion**

Based on an updated set of material data, calculations have been achieved for deriving the evolution of mixed matrix parameters to accurately SAW device at any temperature. The sensor design then must be carried out on the whole temperature range to check the actual sensor response evolution and to guaranty the spectral purity. Respecting these rules allows for effective temperature measurements above 600°C using a 2-resonator based differential sensor.

Acknowledgment

This work is partly supported by the French Ministry of Research and High Education in the frame of the Concours National de Création d'Entreprises Innovantes - CNCEI 2013 and the FEDER project entitled CORCOVADOS, experimental work was partly achieved in the frame of the EC-Russia project called SAWHOT (NMP4-SL-2009-247821)