# Theoretical and experimental investigation of langasite as material for wireless high temperature SAW sensors

S. Sakharov, S. Kondratiev, A. Zabelin
Fomos-Materials
Moscow, Russia
sakharov@newpiezo.com

N. Naumenko
Institute of Steel and Alloys
Moscow, Russia

A. Azarov, S. Zhgoon, A. Shvetsov
Moscow Power Engineering Institute
Moscow, Russia

***Abstract*—Different cuts of langasite were investigated theoretically and experimentally as candidates for high temperature sensors utilizing SAW resonators and reflecting SAW tags. Single port SAW resonators with central frequencies close to 170, 200 and 433 MHz with W, Ir and Pt electrodes of different thickness were fabricated and their characteristics were measured as functions of temperature. An approach to SAW device encapsulation, which helps to avoid stress development during heating to high temperatures, was suggested and tested. The damage of the langasite surface during heating to high temperature is strong in the cut family with Euler angles (0º, 138.5º, ψ), while orientations with Euler angles (0º, 90º, ψ) and (0º, 22º, ψ) were found to be more tolerable to heating. In the latter cut family, two cuts, (0º, 22º, 31.5º) and (0º, 22º, 90º) can provide zero power flow angle and sufficient piezoelectric coupling. COM parameters of SAW resonators with W, Ir and Pt electrodes, including complex reflection coefficient, were calculated as functions of electrode thickness and measured in the wide temperature range. The frequency responses were described by COM equations and the fitted COM-parameters were compared to their simulated values. Resonators show high Q and their performance is perfectly described by COM equations**

***Surface acoustic waves; high temperature sensors;, langasite***

## I. INTRODUCTION

The wireless high temperature sensors are important for many applications including motors and turbines. Among available substrates, langasite and langatite are the most promising due to moderate price, availability of 4” wafers, high temperature melting point and good piezoelectric properties at high temperatures. The development and fabrication of high-temperature SAW sensors [1, 2] with operating temperatures up to 700°C is a complicated task, which includes selection of proper substrate orientation, design of SAW sensor system, fabrication and encapsulation of SAW devices capable to prevent stress at high temperatures, etc. Some of these issues are considered in the present work.

## II. CHOICE OF SUBSTRATE AND CRYSTAL ORIENTATION

The substrate choice is very limited by the palette of piezoelectric substrates which are manufactured in mass production conditions. These substrates are: quartz; lithium niobate and lithium tantalate (LN and LT); the crystal family which includes langasite (LGS) and langatate (LGT) [3].

Quartz and lithium tantalate are excluded from the list of candidates because at high temperature they loose piezoelectric properties. The Curie temperature of LN is very high about 1165°C but the high conductivity above 600°C restricts the possibility of using LN for high temperature sensors.

Langasite and langatate are thus the best candidates. Moreover these crystals have improved piezoelectric properties at high temperature above 600°C [4].

There are few crystal cuts of langasite, with Euler angles (0º, 138.5º, 26.6º), (0º, 140º, 22.5º), (0º, 140º, 25º), which are used in SAW. In addition to nearly zero beam steering, these crystal orientations show low propagation loss and good temperature stability near room temperature. Orientation (0º, 138.5º, 26.6º) also provides low SAW diffraction [4]. These crystal orientations usually demonstrate the effect of natural directivity (NSPUDT).

## III. CHOICE OF ELECTRODE MATERIAL

The melting temperature of electrodes has to be higher than 1500°C to guarantee SAW device operation at high temperature. All such metals have high density which changes the temperature performances and conditions for SAW propagation. The experiments described in [4] show that the temperature behaviour of langasite (0º, 90º, 0º) is close to parabolic with the turnover point between 300-380°C. A significant difference between measurements and results of theoretical calculations with published constants [6] was shown in [4]. We have also observed this difference during our analysis of measurements and theoretical calculation of COM parameters and temperature performance of SAW resonators. On one side, this is due to inaccuracy of physical models and to the use of insufficiently accurate elastic and their temperature properties for dense metals on langasite. On other side, it can be due to inaccuracy of the technological process. Both modeling and fabrication need to be improved.

## IV. EXPERIMENTAL

We have started with readily available cuts of langasite for SAW resonators in order to check the technological process, the resonator electrical and temperature performances and the possibility to fit COM parameters to measurements and to use them for further designs.

An about 433 MHz synchronous resonator design on (0º, 138.5º, 26.6º) cut of langasite was fabricated with 100 nm thick W as a test structure. The aperture was 300 microns; the number of electrodes in IDT and in gratings 191 and 50, respectively, the pitch is equal to 2.974 micron

Figure1 shows that the performance of this synchronous resonator can be described by COM equation with high accuracy. The ratio of the central frequency to 3 dB bandwidth of the S11 deep is about 10000. The depth of S11 is about 20 dB that is sufficient for accurate temperature measurements. The SAW attenuation is quite low. The high electrode resistance (about 25 Ohm series resistance in the equivalent circuit) was observed in these measurements. We expected to see several times lower resistance. The nature of high surface resistance of thin films made with metals such as Ir and Pt on other cuts requires further detailed investigation.

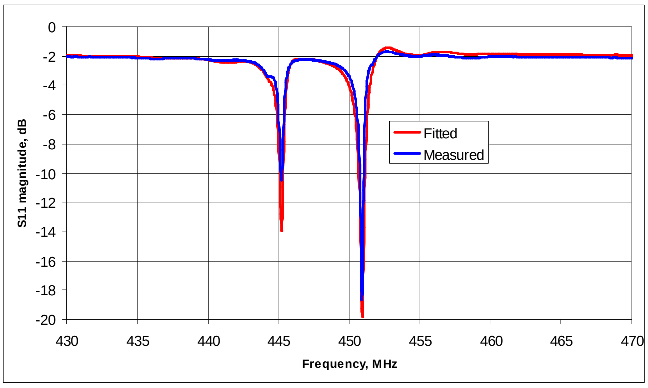


Figure 1. The measurement of S11 of synchronous resonator is in blue and the theoretical fitting s11 is in red.

Figure 1 shows the measurement S11 magnitude of synchronous resonators and the fitting of this measurement to a theoretical model based on COM-equations. As it was mentioned above, this cut of langasite shows NSPUDT effect that creates two resonance deeps. This phenomenon can be considered as a significant advantage. Firstly, this resonator can be used itself as the sensitive element of the differential sensor. We measured the temperature coefficient of frequency (TCF) for both resonances near room temperature and found that the difference in TCF between two resonances is several ppm/°C. Secondly the sensitivity to technological process of high frequency resonance is several times lower than that of the low frequency resonance. It is usually better than the frequency variation of a “hiccup” resonator structure [7] because “hiccup” resonator is not sensitive to the changes in reflection coefficient. This fact has a simple physical explanation: the relative frequency difference between resonances is proportional to the coefficient of reflection. If because of the technological process errors (higher metal thickness) the reflection coefficient becomes higher, then the SAW velocity simultaneously goes down. Thus the frequency increase of the right resonance due to reflection increase is compensated by the velocity decrease.

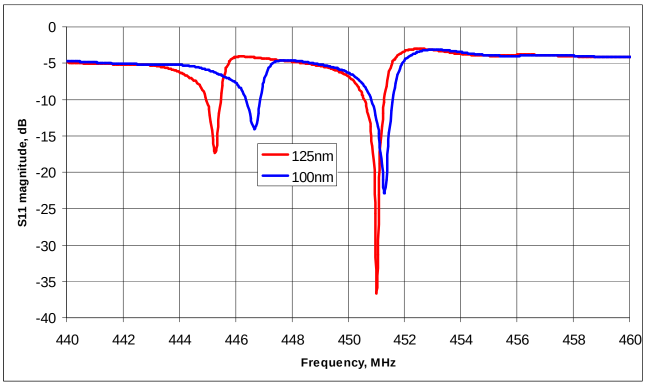


Figure 2. The simulation of S11 of synchronous resonator is in blue for fitted curve in the Figure 1 (100 nm) and the simulation of s11 for larger metal thickness (125 nm) is in red.

Figure2 illustrates this phenomenon for low and high frequency resonance deeps.

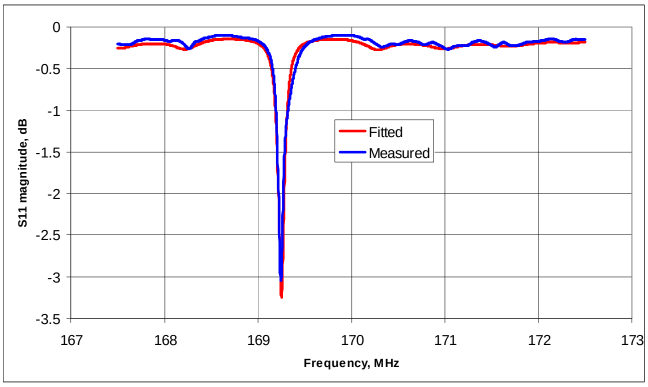


Figure 3. The measurement of S11 of a non synchronous resonator is in blue and the theoretical fitting is in red with Pt electrodes.

We have also designed a resonator layout with one of the reflectors shifted by a quarter wavelength in order to obtain a single resonance in the middle of the Bragg band (similar to “hiccup” resonator response) with a central frequency about 170 MHz. Figure 3 illustrates measured and fitted response of this resonator on langasite (0º, 138.5º, 26.6º) with Pt electrodes.

Another synchronous resonator layout with a central frequency around 200 MHz has been used to characterise (0º, 22º, ψ) and (0º, 90º, ψ) cut family.

Figure 4 shows the result of measurements and fitting for (0º, 22º, 31.5º) cut of langasite. In this case, the reflection coefficient again has a complex value. The Ir thickness is about 50 nm. The thin Ir electrodes determine an about 20 Ohm series resistance in the equivalent circuit. The ratio of the central frequency to 3 dB bandwidth of the S11 deep has the order of several thousands.

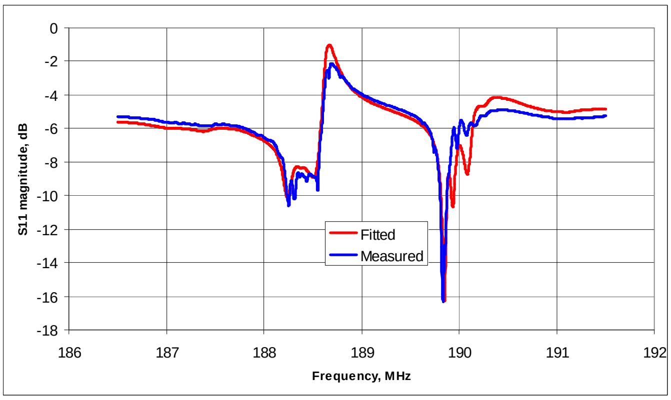


Figure 4. The measurement of S11 of asynchronous resonator is in blue and the theoretical fitting is in red for (0, 22, 31.5) cut of langasite.

Figure 5 shows the result of measurements and fitting for STW cut (0º, 22º, 90º) of langasite. In this case, the reflection coefficient is real. The resonator layout is identical to that of the previous resonator; the metal thickness is 120 nm.

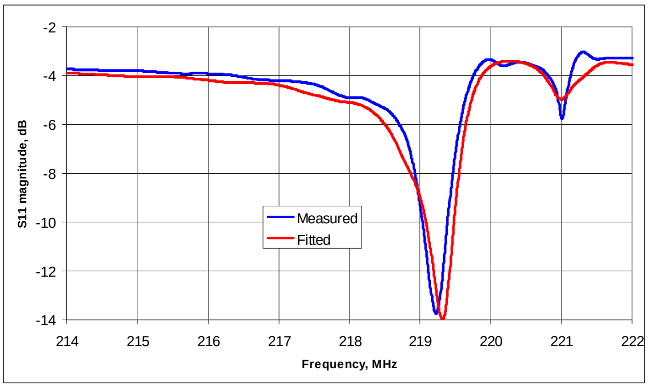


Figure 5. The measurement of S11 of a synchronous resonator is in blue and the theoretical fitting is in red for STW cut of langasite.

Resonators made on (0º, 90º, 0º) (Y-cut) of langasite have shown very low reflection coefficient with thin (50 nm) Ir electrodes and similar temperature behaviour to published in [4], while same resonators on langasite (0º, 90º, 32º) had similar temperature behaviour and sufficient reflection coefficient for resonator operation.

For five orientations of langasite, which show sufficiently high electromechanical coupling combined with zero or small beam steering angle, the measured dependences of relative frequency deviation Δf/f versus temperature were compared with simulated dependences. Simulations were made with iridium electrodes of thickness 100 nm or 120 nm (according to experiments for different cuts) and aspect ratio a/p=0.5, while the pitch of the grating was p=6,584 μm. Electrodes were assumed to be of rectangular profile. The constants measured by Bungo [6] were used for simulations, which provide the best agreement with experiments, compared to other material sets, at least up to the temperature 250ºC.

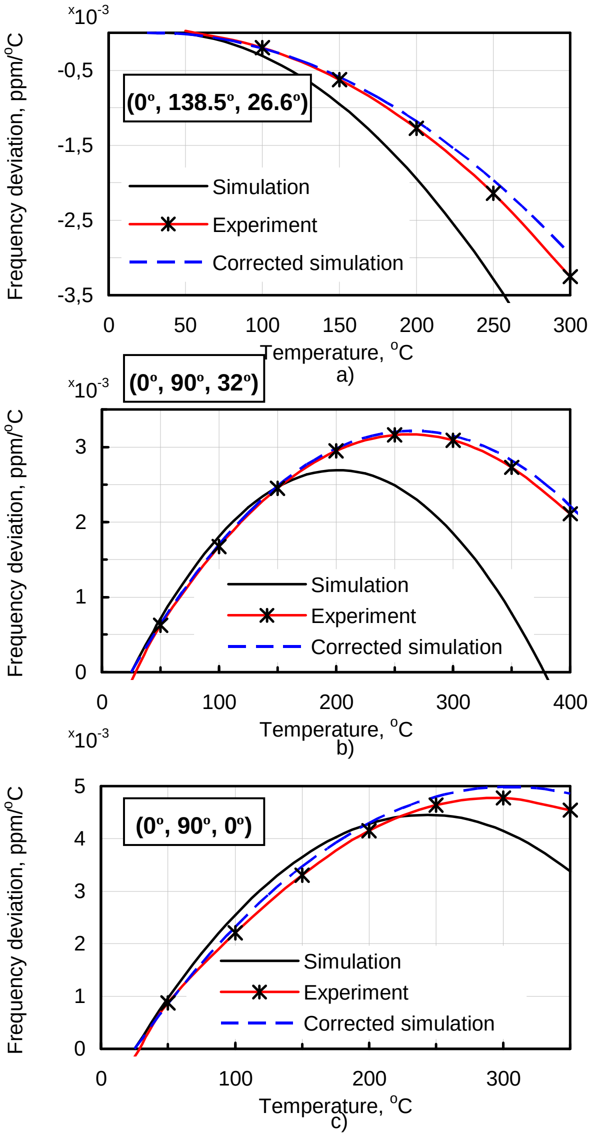


Figure 6. Simulated and experimental frequency deviation versus tempetature dependences in three orientations of langasite with Ir electrodes, h/P=0.0076 ($h_{Ir}$=100 nm, p=6.584 μm; P=2p)

Figure 6 compares experimental and simulated temperature characteristics for three orientations: (0º, 138.5º, 26.6º), (0º, 90º, 32º) and (0º, 90º, 0º), with the same Ir electrode thickness. The difference between measured and calculated functions Δf/f(T) was extracted for each orientation and fitted with 2-nd order polynomials with respect to deviation of temperature from $T_0$=25ºC. If this difference is included in simulation, as "corrective function", e. g. instead of thermal extension coefficient characterized by polynomial dependence on temperature, then it is possible to obtain better agreement between experimental and simulated dependences Δf/f(T) for each orientation, especially for estimation of turnover temperature.

Corrective functions obtained for three orientations are shown in Figure 7. For the analyzed cuts, they look close to each other and can be referred to insufficient accuracy of temperature coefficients of LGS constants in wide range of temperatures or to the temperature dependence of Ir constants.

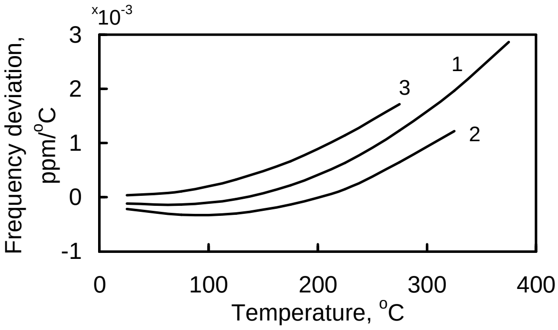


Figure 7. Corrective functions for three orientations extracted from comparison between experimental and simulated temperature dependences: 1 -(0º, 138.5º, 26.7º) , 2 -(0º, 90º, 32º), , 3 - (0º, 90º, 0º).

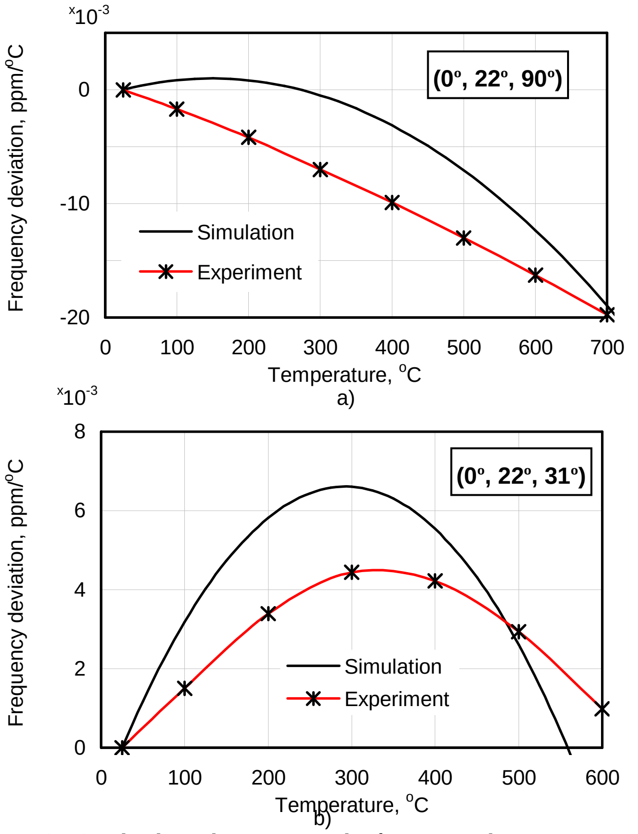


Figure 8. Simulated and experimental frequency deviation versus tempetature dependences in two orientations of langasite with Ir electrodes, h/P=0.0091 ($h_{Ir}$=120 nm, p=6.584 µm, P=2p)

For two orientations, in which SAW has quasi-bulk nature, with mostly SH-type of polarization, (0º, 22º, 90º) and (0º, 22º, 31.5º), the difference between simulated and measured dependences Δf/f(T) is much larger and cannot be referred to inaccuracy of temperature coefficients in wide range (Fig.8).

In order to protect the electrode structure from environmental damage we have fabricated covers from the same langasite orientations as the resonator substrates and fixed them by diffusion bonding to the resonators. The assemblies have survived heating to 800ºC without separation.

## Conclusion

Langasite has an essentially non-linear temperature behavior, close to parabolic with the turnover point depending on the substrate orientation. Some orientations, such as (0º, 22º, 31.5º) have a vertex at about 400ºC – in the middle of available operation temperature range. They may serve as a reference for measurement in wide temperature range but at the same time they present relatively high TCF at low and room temperature as well as at high temperature thus enabling development of temperature sensors with high sensitivity in these ranges. The (0º, 22º, 90º) cut of langasite parabolic dependence has a vertex at very low temperatures and shows a close to linear branch from room to high temperatures serving universally as a temperature sensor in all frequency ranges. These two orientations differ by the propagation direction on the same cut and may be used together to create a pair of sensors with different temperature behavior serving as a reference to each other. The frequency difference is then the parameter determining the measured temperature.

In systems restricted to work in ISM bands, the application of resonator based systems determine the need in relatively low TCF in order to keep the frequency inside a narrow band and the solutions with resonators on langasite require the division of measured range in several sub ranges.

Application of orientations (0º, 22º, 31.5º) and (0º, 22º, 90º) is preferable compared to commonly used in filters (0º, 138.5º, 26.6º) cut, due to higher tolerance to heating.

## Acknowledgment


This research has been performed under the SAWHOT coordinated project (partially funded by the Ministry of Education and Science of the Russian Federation).


## References


[1] S. Ballandras, W. Daniau, G. Martin, and P. Berthelot, "Wireless Temperature Sensor using SAW Resonators for Immersed and Biological Applications", in Proc. IEEE Ultrason. Symp. pp.445-448, 2002.

[2] J.A. Thiele, and M. Pereira da Cunha, "Platinum and Palladium High-Temperature Transducers on Langasite", IEEE Transactions UFFC, vol. 52, no. 4, pp. 545-549, 2005.

[3] http://www.newpiezo.com

[4] T. Aubert, F. Sarry, O. Elmazria, L. Bouvot, B. Assouar, P. Nicolay, M. Hehn, “Extraction of COM parameters on Pt/LGS for high temperature SAW sensor”, IEEE Ultrasonics Symposium, 2008, pp.820-823.

[5] N.F.Naumenko, L.P.Solie, "Optimal cut of langasite for high performance SAW devices", IEEE Ultrasonics Symposium, 1999, pp.243-248.

[6] A. Bungo, C. Jian, K. Yamaguchi, Y. Sawada, R. Kimura, S. Uda, “Experimental and theoretical analysis of SAW properties of the Langasite Substrate with Euler Angle (0°,140°,θ), IEEE Ultrasonics Symposium, 1999, pp 231-234.

[7] Wright P.V., “The natural single-phase unidirectional transducer a new low loss SAW transducer”, IEEE Ultrasonics Symposium, 1985, pp. 43-48.