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SAW-Relevant Material Properties of Langasite in the Temperature Range from 25 to 750 °C: New Experimental Results

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***Abstract*— The aim of this work is to determine the acoustical parameters of langasite up to the highest possible point of temperature. This paper presents measurements of transfer functions for delay lines on langasite at frequencies ranging from 150 MHz to 1 GHz, at temperatures from 25 to 750°C. Two cuts with Euler angles (0°, 138.5°, 26.6°) and (0°, 30.2°, 26.6°) have been studied. The devices were fabricated using langasite as substrate, with two different platinum (Pt) layer heights (45 nm and 75 nm), on a zirconium (Zr) adhesion layer (4 nm). A special signal processing algorithm utilizing cross-correlation was implemented in MATLAB and used for the analysis of measured data. The material parameters relevant for SAW devices, such as phase velocity, propagation loss, and electromechanical coupling coefficient, have been determined as a function of temperature.**

Keywords-component; SAW, langasite, high temperature, material properties, acoustical parameters.

I. INTRODUCTION

For increasing demands by industry for wireless sensor applications up to 1000°C and harsh environments, surface acoustic waves (SAW) devices – for example SAW-ID tags and sensors – have advantages in comparison to devices based on other technologies [1]-[4].

Unfortunately, traditional SAW materials like quartz and lithium niobate cannot be used at temperatures higher than about 570°C or 350°C, respectively, because of phase transition or decomposing effects. The relatively new piezoelectric material langasite ($La_3Ga_5SiO_{14}$, LGS) preserves its piezoelectric properties up to its melting point at about 1470°C and seems to be applicable for SAW devices at high temperatures [5]-[7]. The electromechanical coupling coefficient of langasite is about three times higher than that of quartz [8].

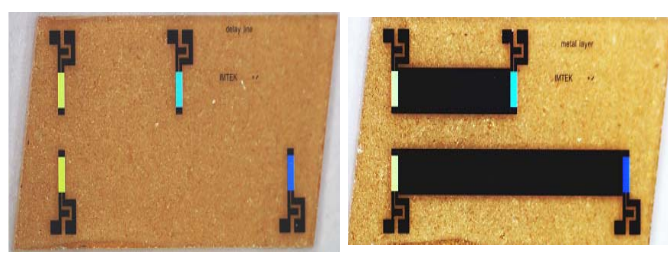
This paper presents transfer function measurements of test structures on LGS up to 750ºC and the analysis of measured data using a special signal processing algorithm developed to obtain a precise evaluation of SAW properties of LGS. Finally, the results are discussed.

II. MEASURMENTS

A. *Chip Design*

The investigated properties of LGS are phase velocity v_p, propagation loss α and coupling coefficient k^2. Two crystal cuts of langasite (0º, 30.1º, 26.6º) and (0º, 138.5º, 26.6º) were used for the measurements. Both of them have a zero power flow angle [6], [8].

In order to calculate the group velocity v_{gr}, and coupling coefficient k^2 delay lines of four types were designed – short and long, with free and metallized propagation path [9],[10] (Fig. 1). Each delay line consists of two interdigital transducers (IDT). One IDT serves as a sender and the other as receiver of the SAW. The delay lines are fabricated on langasite as substrate with two different platinum (Pt) layer heights (45 nm and 75 nm), on top of a zirconium (Zr) adhesion layer (4 nm).



a) b)

Figure 1. Chips with free (a) and with metallized (b) surface between IDT.

All IDTs have the same design. They are multi electrode transducers with double spatial sampling [11]. Their transfer function S_{21} has four passbands (harmonics H_1, H_3, H_5, and H_7) with center frequencies at about f_1=150 MHz, f_3=450 MHz, f_5=750 MHz, and f_7=1050 MHz, respectively. The length of both delay lines (DL) is designed such, that the delays of their impulse responses are approximately 1 µs (short DL) and 1.9 µs (long DL) (Fig. 2).

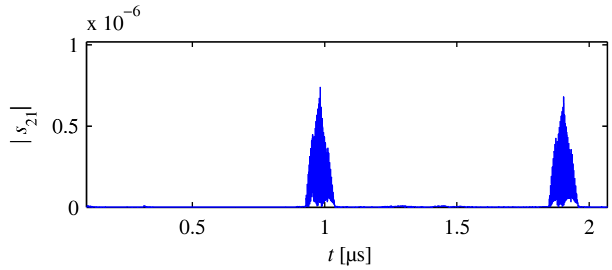


Figure 2. Superposed impulse responses of short and long delay lines (free propagation path).

B. Measurment Setup

The chip is mounted on a holder and is connected to the RF-flange of the high temperature oven via two rigid coaxial cables. The other side of the RF-flange is connected by standard RF coaxial cables to the network analyzer, which measures the transfer function S_{21} in temperature steps of 5 K. Before starting measurements, the atmosphere inside the oven is changed to nitrogen. The heat up was done with a slow continuous ramp of 50K/h up to the final temperature of 800°C.

C. Signal Processing

A special signal processing algorithm is developed for precise analysis of measured data. The algorithm works in two stages. In the first stage, for every measured temperature point the center frequencies and the time difference between impulse responses of short and long delay lines are determined. In the second stage the acoustical material parameters of the related langasite cut are calculated as a function of temperature.

The algorithm starts by reading the measured data and applies a window function (Fig. 3).

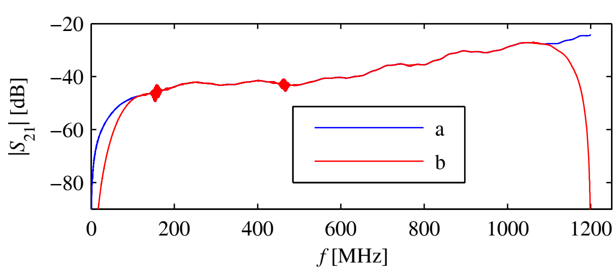


Figure 3. Raw data (a) and corresponding data after applying window function (b).

The signal is transformed to time domain to get the impulse response of each delay line (Fig. 2). By gating the two pulses separately and transforming both to frequency domain, the transfer function of each delay line is obtained (Fig. 4).

The transfer function S_{21} consists of four harmonics according to the double sampled IDT. At high temperatures, the harmonics H_5 and H_7 disappear completely, so just the harmonics H_1 and H_3 can be used for further data processing (Fig. 5).

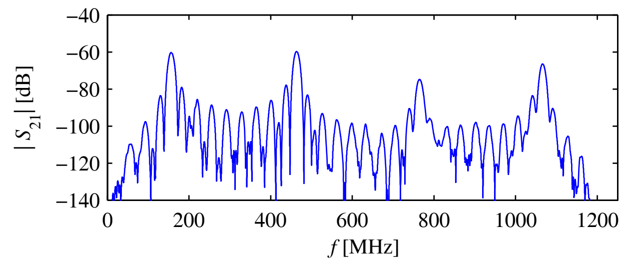


Figure 4. Transfer functions of a delay line.

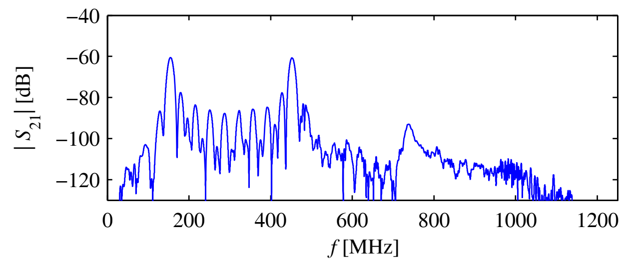


Figure 5. Transfer functions of a metallized chip at 548ºC.

By searching the maximum of each harmonic, the center frequencies were calculated and corrected, using the phase slope in time domain at the particular frequency. This step is done for all harmonics of short and long delay lines. The relative measurement of time delay difference eliminates the influence of IDTs. Each harmonic was transformed to time domain to get the impulse response at this harmonic frequency. Two methods were used to determine the time difference Δt between two delay lines.

The first method starts with cross correlating the impulse responses of short (h_s) and long (h_l) delay lines. This is followed by fitting the resulting signal to a 4th order polynomial to find the maximum, which gives directly Δt (Fig. 6).

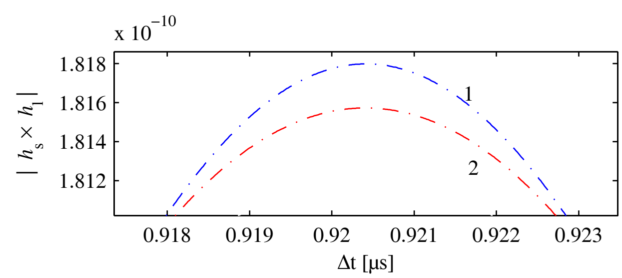


Figure 6. Original (1) and fitted (2) cross correlation of two impulse responses (h_s ,h_l).

The second method uses the fact that the impulse response of each delay line in time domain is a triangle. So the time response of each pulse is calculated by a linear fit of both rising and falling edge of the triangle, and finding the time at the point of intersection (Fig. 7).

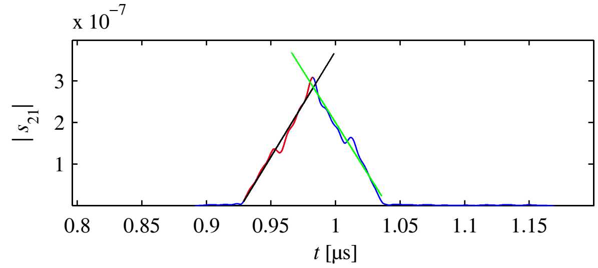


Figure 7. Fit of two slopes to find accurate postion of a pulse.

Using the determined time difference Δt_i at each frequency f_i and constant length difference ΔL between two delay lines, for all temperature points, the group velocity $v_{gr,i}$ is computed as

$$v_{gr,i} = \frac{\Delta L}{\Delta t_i}. \qquad (1)$$

In the case of the free delay line, the group velocity $v^{f}_{gr,i}(T,f)$ is a function of temperature T and frequency f. The group velocity $v^{m}_{gr,i}(T, f, h/\lambda)$ of the metallized delay line has an additional dependence on metallization height h and wavelength λ. The phase velocity can be obtained by evaluating the group velocity at $f = 0$ Hz and $h = 0$ m. This will yield the phase velocity v_{ph} as function of temperature on the free and the metallized surface.

The propagation loss α_i at harmonic frequencies was calculated using

$$\alpha_i = \frac{1}{\Delta t_i} \cdot 20 \cdot \lg \frac{\left|S_{21,i}^{long}\right|}{\left|S_{21,i}^{short}\right|}, \qquad (2)$$

where $|S_{21,i}^{long}|$ and $|S_{21,i}^{short}|$ are the maxima of the transfer functions of short and long delay lines at the corresponding frequency f_i in frequency domain.

The electromechanical coupling coefficient was calculated from the values of the phase velocities v_m and v_0 on the metallized and free surface using Ingebrigtsen's formula [12]

$$k^2 = -2\frac{v_m - v_0}{v_0}. \qquad (3)$$

III. Results

A. Materials at High Temperature

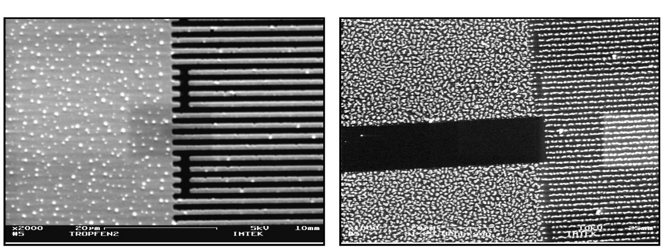


Figure 8. (a) Beginning of dewetting at 730°C (b) IDT at 800°C.

Temperatures above 750°C cause chip failures. This is due to the temperature effect on the Zr/Pt-metallization. Dewetting started at a temperature of about 730°C (Fig. 8a). Above 750°C the whole Zr/Pt-metallization decomposes into droplets (Fig. 8b). This effect is presumably due to diffusion and recrystallization of the layer.

B. Acoustic Properties of LGS

1) Group and Phase Velocity, and Coupling Coefficient

The group velocities $v^{f}_{gr,i}(T,f)$ for free surface of the two LGS cuts as a function of temperature are shown in figures 9 and 10. Both cuts show a parabolic dependance of $v^{f}_{gr,i}(T,f)$, whereas the first cut (0º, 138.5º, 26.6º) has its maximum approximately at room temperature (fig. 9) and the latter (0º, 30.1º, 26.6º) at about 360°C (Fig.10).

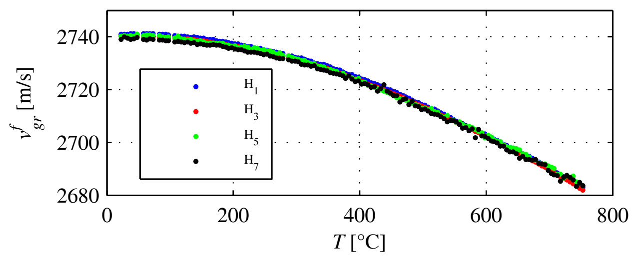


Figure 9. Group velocity on free surface, cut (0º, 138.5º, 26.6º).

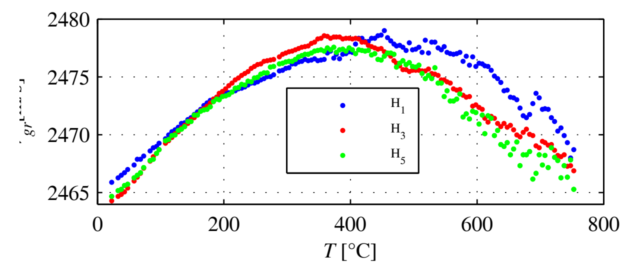


Figure 10. Group velocity on free surface, cut (0º, 30.1º, 26.6º).

The extracted phase velocities v_0 and v_m on free and metallized surfaces for the cut (0º, 138.5º, 26.6º) are shown in Fig. 11. The corresponding coupling coefficient k^2 is calculated accordingly to (3) and plotted in Fig. 12.

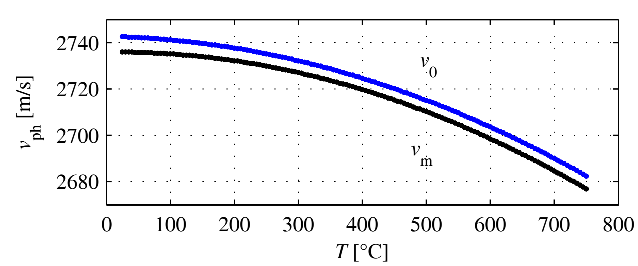


Figure 11. Phase velocityon on free and metallized surface, cut (0º,138.5º,26.6º).

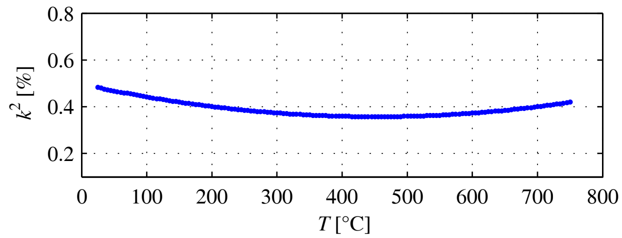


Figure 12. Coupling coefficient, cut (0º, 138.5º, 26.6º).

2) *Propagation Loss*

The propagation losses α_l on free and metallized surfaces of langasite with cut (0º, 138.5º, 26.6º) are shown in Fig. 13 and Fig. 14. For cut (0º, 30.1º, 26.6º) the propagation loss on free surface is plotted in Fig. 15.

An anomalous behavior of propagation loss was found between 300°C and 700°C, where a local maximum of propagation loss at about 500°C is observed. The propagation loss on metallized surface increased dramatically above 450°C (Fig. 14). Comparing the propagation losses on the free surface of both investigated cuts, the propagation loss on cut (0º, 30.1º, 26.6º) is about four times larger.

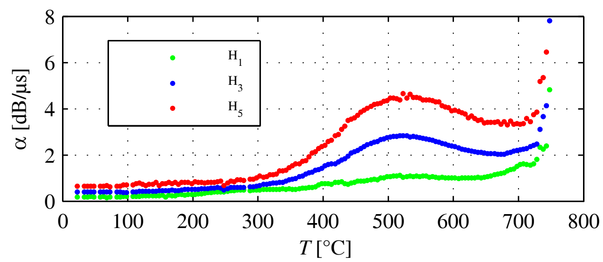


Figure 13. The propagation loss on free surface, cut (0º, 138.5º, 26.6º).

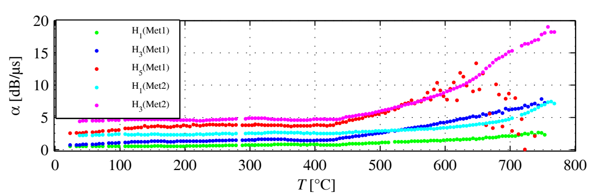


Figure 14. The propagation loss on metallized surface,cut (0º, 138.5º, 26.6º).

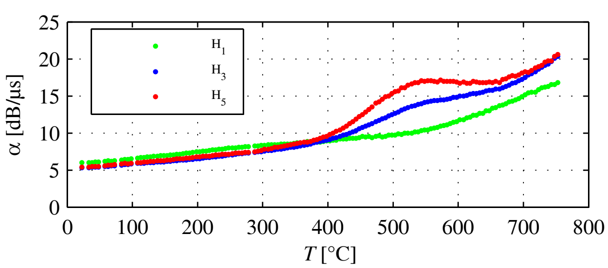


Figure 15. The propagation loss on free surface, cut (0º, 30.1º, 26.6º).

IV. CONCLUSION

In this work, the phase velocity, propagation loss and electromechanical coupling coefficient for crystal cuts of langasite with Euler angles (0º, 30.1º, 26.6º) and (0º, 138.5º, 26.6º) have been investigated. These surface acoustic wave properties were determined as function of temperature up to 750°C. Furthermore, the analysis algorithm was described and the effect of temperature on the used Zr/Pt-metallization was explained.

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