Transactions of the Materials Research Society of Japan 29[4] 1093-1096 (2004)

Microwave Characterization of (La,Sr)(Al,Ta)O_3 Using TE_{011} Mode Dielectric Resonator

M. V. Jacob[1], J. Mazierska[1] and J. Krupka[2]
[1]Electrical and Computer Engineering, James Cook University, Townsville, Q4811, Australia
Mohan.Jacob@jcu.edu.au
[2]Instytut Mikroelektroniki i Optoelektroniki Politechniki Warszawskiej, Koszykowa 75, 00-662 Warszawa, Poland.

Abstract- The permittivity and loss tangent of a dielectric material can be estimated from precise measurement data of the Q-factor and resonant frequency of a dielectric resonator containing the material under test. We have characterized an (La,Sr)(Al,Ta)O_3 (LSAT) single crystal of the cylindrical shape using TE_{011} mode dielectric resonator in two enclosures at a frequency of 15.5 GHz at temperatures from 15 K to 293 K and an LSAT planar sample at 9.7 GHz using a post cryogenic $TE_{01\delta}$ resonator. Our measurements have shown that permittivity of LSAT is in the vicinity of 23 and exhibits a peak at temperature of 190 K. We have also studied the temperature coefficient of frequency of the LSAT substrate. Due to the weaker temperature dependence of permittivity of LSAT substrates, HTS devices and circuits fabricated on LSAT can be more stable than on Lanthanum Aluminate.

Key Words: Dielectric Resonator, LSAT, permittivity, loss tangent

1. INTRODUCTION

Among the popular dielectric materials LSAT $(LaAlO_3)_{0.3}(Sr_2AlTaO_6)_{0.7}$ is a comparatively newly developed (1999) material [1]. Table I shows some of the physical and chemical properties of LSAT crystal. The main application of LSAT is as a substrate material for GaN thin films [2, 3]. LSAT has a better crystal structure than $LaAlO_3$ (no twin and domain structure), so that a high quality High T_c Superconducting (HTS) films can be grown on this substrate [1]. LSAT has lower melting point than $LaAlO_3$ (LAO) and can be grown by Czochralski technology at lower cost; therefore it may be expected to replace LAO as a common single crystal substrate for epitaxial YBCO thin films for superconductive devices.

Table I Chemical and Physical properties of LSAT crystal

Crystalline System	Tetragonal(4m)
Space group	I 4
Molecular Formula	$(LaAlO_3)_{0.3}(Sr_2AlTaO_6)_{0.7}$
Growth Method	Czochralski
Lattice Constant	a=b=5.468, c=7.729, a=b=c=90^0
Density	6.74g/cm3
Thermal Expansion Coefficient	$10.6\times10^{-6}/^0C$
Dielectric Constant	~ 22
Hardness	6.5 Mohs
Melting Point	1840 ^0C
Color	None or light yellow

The microwave properties of LSAT cylindrical samples have been measured before as a function of temperature at 8.8 GHz using a post dielectric resonator [8]. The goal of this paper is to characterise LSAT rods using TE_{011} Dielectric Resonator and LSAT substrates as a function of temperature. The paper also presents computation of the temperature coefficient of frequency as a function of temperature. We have used the multifrequency Transmission Mode Q-Factor (TMQF) technique [4] for data processing to ensure high accuracy of computed values of ε_r and tanδ.

II. DIELECTRIC RESONATORS USED

A TE_{011} mode dielectric resonator [5] consists of a copper cavity and a dielectric rod of the same height as that of the cavity, as schematically shown in Fig. 1. The end plates are typically copper but to achieve high resolution HTS thin films can be used as the end plates [6,7]. Hence we have carried out measurements using the fully copper cavity and also with the HTS end walls. The LSAT rod of diameter (D=2a) of 5.01mm and height L of 3.08mm was sandwiched between the two end plates (copper or superconducting thin films). The cavity diameter (2b) was 9.5 mm.

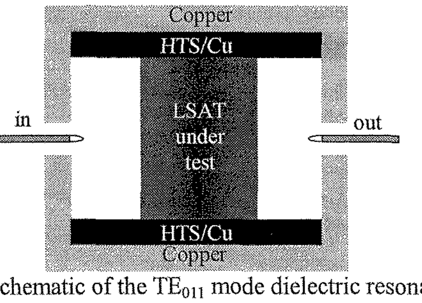

Fig.1. Schematic of the TE_{011} mode dielectric resonator.

The real part of relative permittivity ε_r was determined from measurements of the resonant frequency of the HCDR with the LSAT sample as the first root of the following transcendental eq. [8]:

$$k_{\rho1}J_0(k_{\rho1}b)F_1(b)+k_{\rho2}J_1(k_{\rho1}b)F_0(b)=0 \qquad (1)$$

where:

$$F_0(\rho)=I_0(k_{\rho2}\rho)+K_0(k_{\rho2}\rho)\frac{I_1(k_{\rho2}a)}{K_1(k_{\rho2}a)}$$

$$F_1(\rho) = -I_1(k_{\rho 2}\rho) + K_1(k_{\rho 2}\rho)\frac{I_1(k_{\rho 2}a)}{K_1(k_{\rho 2}a)}$$

$$k_{\rho 1}^2 = \frac{\omega^2 \varepsilon_r}{c^2} - k_z^2, \quad k_{\rho 2}^2 = k_z^2 - \frac{\omega^2}{c^2}, \quad k_z = \pi / L$$

and ω is the angular frequency, c is velocity of light, ε_o is free space permeability, ε_r is real relative permittivity of the sample and J_0, J_1, I_0, I_1, K_0, K_1, denote corresponding Bessel and Hankel functions.

The loss tangent $\tan\delta$ of LSAT was computed from the measured Q_0-factor of the resonator on the basis of the loss tangent equation [8]:

$$\tan\delta = \frac{1}{\rho_e}\left[\frac{1}{Q_0} - \frac{R_{SS}}{A_S} - \frac{R_{SM}}{A_M}\right] \quad (2)$$

where Q_0 is the unloaded Q-factor of the entire resonant structure, R_{SS} and R_{SM} are the surface resistance of the superconducting and the metallic parts of the cavity respectively, A_S and A_M are the geometric factors of the superconducting (end wall) and metallic (lateral wall) parts of the cavity and ρ_e is the electric energy filling factor.

Geometric factors A_S, A_M, and ρ_e to be used in (2) were computed using incremental frequency rules as follows:

$$A_S = \frac{\omega^2 \mu_0}{4} / \frac{\partial\omega}{\partial L} \quad (3)$$

$$A_M = \frac{\omega^2 \mu_0}{2} / \frac{\partial\omega}{\partial a} \quad (4)$$

$$p_e = 2\left|\frac{\partial\omega}{\partial\varepsilon_r}\right|\frac{\varepsilon_r}{\omega} \quad (5)$$

Computed values of the geometrical factors and the energy filling factors of the dielectric resonator containing LSAT and Sapphire rods are given in Table 2. The Sapphire dielectric rod resonator was needed was for measurements of surface resistance of Copper and Superconducting thin films required for calculating $\tan\delta$.

Table 2 Geometrical factors and the energy-filling factor of the LSAT and Sapphire resonators.

Dielectric Rod	LSAT	Sapphire
Frequency	15.5 GHz	24.6 GHz
A_M	16121	22319
A_S	188.1	280.6
ρ_e	0.98	0.97

III CHARACTERISATION OF LSAT SINGLE CRYSTAL CYLINDRICAL SAMPLES

Microwave characterisation of LSAT rods was performed using the TE_{011} mode resonator enclosed in two cavities (fully copper and with HTS endplates) as described in the previous section. The resonator was cooled down to approximately 12 K using a close cycle refrigerator (APD-204 SL). The S-parameters were measured around the resonance frequency of 15.5GHz using the Vector Network Analyser (HP 8722C) as function of temperature from 15K to 295K using the copper cavity and from 14K to 82K using the cavity with superconducting end plates. The S-parameter data was processed using the Transmission Mode Q-Factor (TMQF) technique to remove losses in cables, crosstalk and phase delay [4].

Fig. 2 shows measured unloaded Q-factor as a function of temperature for two tests. The loss tangent of the LSAT material was calculated using Eq. (2) and is shown in Fig. 3. The lowest losses are observed at 15K (5×10^{-5}) and the highest losses were measured at 160 K (4.9×10^{-4}). The difference obtained in $\tan\delta$ measurements using the Cu cavity and the HTS cavity is approximately 4% and is due to larger measurements errors in the copper cavity.

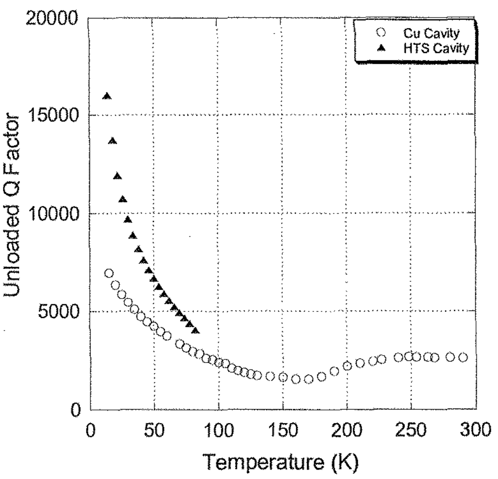

Fig.2 Unloaded Q_o-factor of LSAT at 15.5 GHz vs temperature.

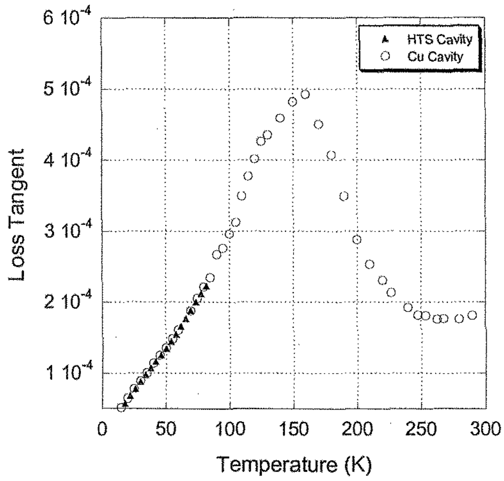

Fig. 3 Loss tangent of LSAT at 15.5 GHz vs temperature

Fig. 4 shows measured resonance frequencies of the LSAT resonators for differing temperatures and the computed permittivity is presented in Fig. 5. The permittivity values vary between 22.94 and 23.17 in the temperature range from 15K to 295K with a peak at 190K. Maximum difference in the ε_r values between the two measurements we carried out using the Cu and the HTS cavity is 0.1%.

Similar variations of loss tangent and permittivity were previously observed in [8] at 8.8GHz frequency but reported permittivity values were between 22.75 and

22.9 [9]. Table 3 gives a comparison of the obtained results with previously reported ε_r and $\tan\delta$ values for LSAT rods. Our measurements are in good agreement with the reported room temperature permittivity values of 23.25 and 23.07 and the corresponding loss tangent 1.47×10^{-4} and 1.83×10^{-4} in [10].

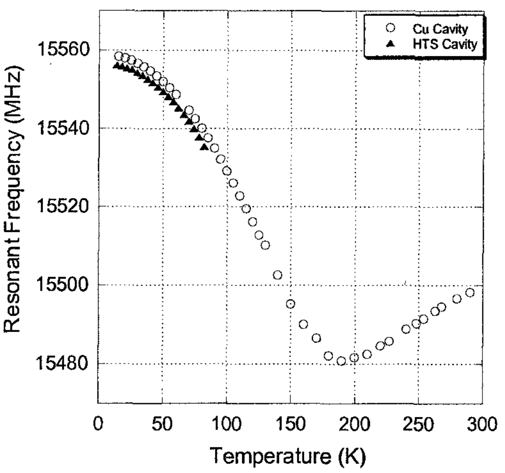

Fig. 4 Resonant frequency of LSAT vs temperature.

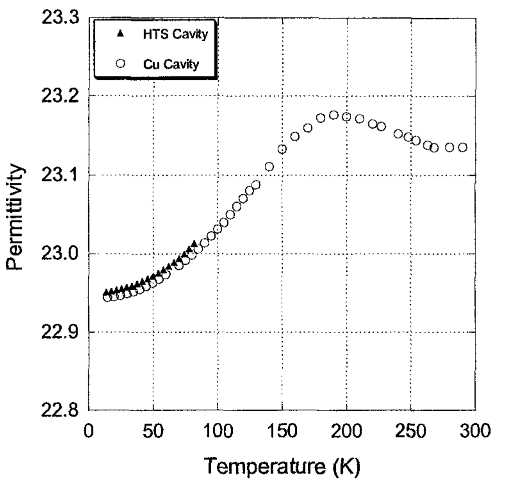

Fig. 5 Permittivity of LSAT at 15.5 GHz vs temperature without taking into account of the coefficient of linear thermal expansion of the material.

Table 3 Comparison of ε_r and $\tan\delta$ values of LSAT

Temperature	ε_r	$\tan\delta$	Ref.
290 K	22.8	5×10^{-5}	[9]
	23.25	1.47×10^{-4}	[10]
	23.07	1.83×10^{-4}	This Paper
	23.13	1.8×10^{-4}	This Paper
190 K	22.9	6×10^{-4}	[9]
	23.17	3.5×10^{-4}	This Paper
50 K	22.75	1×10^{-4}	[9]
	22.97	1.3×10^{-4}	This Paper

Microwave resonators and filters made for the narrow band operation of wireless communication networks require stable resonant frequency despite changes in environmental conditions. The shift in resonant frequency of a dielectric resonator depends on the coefficient of linear thermal expansion and the temperature coefficient of permittivity of a dielectric materials used [11]. The temperature coefficient of resonant frequency (τ_f) of the dielectric resonator, temperature coefficient of permittivity (T_ε) and the linear expansion coefficient (α) of the dielectric material can be related as follows [12]:

$$\tau_f = A_\varepsilon \tau_\varepsilon + A_d \alpha + \tau C_x \qquad (6)$$

where: $A_\varepsilon = \frac{\varepsilon_r}{f_0}\frac{\Delta f_0}{\Delta\varepsilon_r}$ and $A_d = \frac{D}{f_0}\frac{\Delta f_0}{\Delta D} + \frac{L}{f_0}\frac{\Delta f_0}{\Delta L}$ and

τC_x describes temperature properties of a HC cavity and can be considered 0 if dimensions of the cavity remains constant with changes in temperature. From theoretical analysis of the resonant structure one can estimate the values of A_ε and A_d and their values are approximately -0.5 for A_ε and 1.0 for A_d [12].

From the measured resonant frequency of the LSAT dielectric resonator we have calculated the τ_f using the equation:

$$\tau_f = \frac{f_0 - f_{0T}}{f_0}\frac{10^6}{\Delta T} \qquad (7)$$

where f_0 and f_{0T} are the resonant frequency at room temperature and at temperature T respectively.

Fig. 6 shows the measured temperature coefficient of resonant frequency of LSAT dielectric resonator as a function of temperature. The τ_f exhibits a maximum of 12.5 ppm/K at 220 K and -14.5 ppm/K at 40 K and 0 at 145 K.

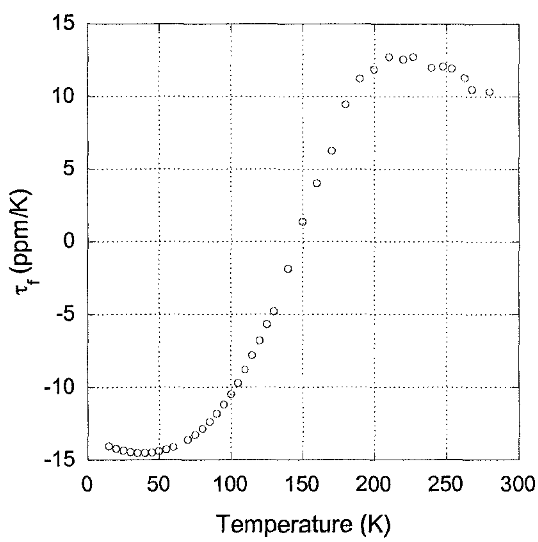

Fig. 6 τ_f of LSAT rod vs temperature.

IV. CHARACTERISATION OF LSAT SUBSTRATE

We have characterized LSAT single crystal substrate of thickness 0.5 mm using a cryogenic post resonator with High Temperature Superconducting plates resonating at 9.7GHz [13]. The measurement procedure with the post resonator was the same as described in section III. The real relative permittivity of the substrates under test has been computed numerically from f_{res} using the rigorous electromagnetic modeling of the cryogenic post resonant structure using the Rayleigh-Ritz technique. Computed values of ε_r of the tested substrate were equal to 22.8 as shown in Fig. 7. Measured value of ε_r of the LSAT substrate is about 0.7% lower than for the cylindrical sample, which is from a different manufacturer.

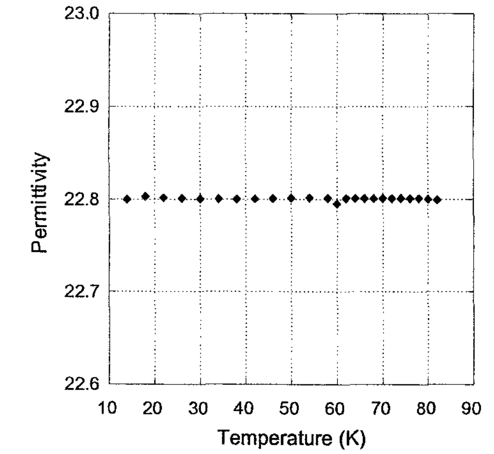

Fig. 7 Measured ε_r of a LSAT substrate at 9.7 GHz.

The loss tangent of the substrate for varying temperatures from 13K to 82K computed from the measured Q_o-factor as described in [13] is presented in Fig. 8. Measured values of tanδ vary between $1.1X10^{-4}$ and $2.5X10^{-4}$ and are higher by approximately 10% as compared with tanδ for the LSAT rod.

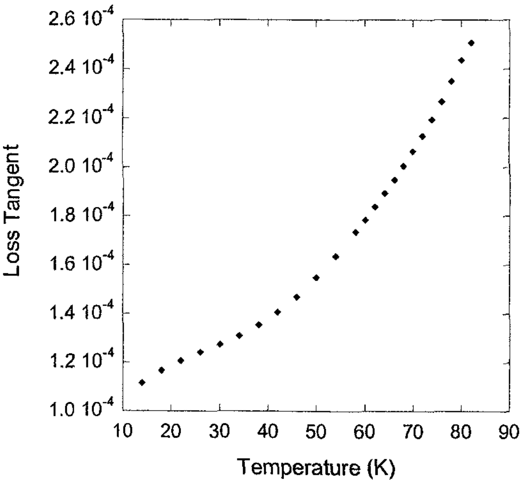

Fig. 8 Measured tanδ of LSAT substrate at 9.7 GHz.

IV CONCLUSIONS

We have precisely measured the perpendicular component of permittivity and loss tangent of $(La,Sr)(Al,Ta)O_3$ single crystal cylindrical and planar samples. Average variations of frequency of the LSAT resonator with temperature of approximately 0.44 ppm/K was obtained and calculated values of the temperature coefficient of resonance frequency varied between –15 ppm and 13 ppm. The measured values of ε_r at 15 K, 190 K and 290 K were 23.09, 23.31 and 23.13 and the corresponding loss tangent values were 5×10^{-5}, 3.5×10^{-4} and 1.7×10^{-4} respectively. The obtained permittivity values of LSAT were close to that of $LaAlO_3$ (approximately 23) and exhibited a peak at temperature of 190 K. The total deviation in ε_r of LSAT was less than 0.25% for the cylindrical sample and 0.03% for the planar sample in the temperature range 15–82K. The total deviation in ε_r in the temperature range 15-295 K for LSAT and $LaAlO_3$ was less than 1% and 1.5% [9] respectively.

LSAT substrate exhibited permittivity of approximately 22.8 and the loss tangent between 1.1×10^{-4} and 2.5×10^{-4} in the temperature range from 15 to 82K.

Due to smaller temperature dependence of permittivity of LSAT dielectrics compared to LAO, HTS devices and circuits depositeded on LSAT substrates can be more stable than on $LaAlO_3$. Also LSAT single crystals are twin-free and hence LSAT could be an excellent substrate material for fabricating High T_c superconducting thin films.

ACKNOWLEDGEMENTS

Authors are grateful for the financial support received from the ARC A00000799. MVJ also acknowledges the JCU CRIG.

REFERENCES

1. [online] www.physoe.com/english/e-010207-LSAT/e010207.htm Crystal Specifications:
2. T. Lukasiewicz et al, 2002, Journal of Crystal Growth **237-239** pp. 1118-1123
3. H. Sakowska et al. 2001 Crystal Research Technology **37** 851-858
4. K. Leong and J. Mazierska 2002 IEEE Transactions on Microwave Theory and Technique, **50** 2115-2127.
5. Y. Kobayashi, M. Katoh 1985 IEEE Transactions on Microwave Theory and Techniques **33** 586-592.
6. M. V. Jacob, J. Mazierska, K. Leong and J. Krupka, 2002 IEEE Transactions on Microwave Theory and Tech. **50** 474-480.
7. M. V. Jacob, J. Mazierska, D. Ledenyov and J. Krupka 2003 European Journal of Ceramic Society.
8. J. Krupka, M. Klinger, M. Kuhn, A. Baranyak, M. Stiller, J. Hinken and J. Modelski 1993 IEEE Transactions on Applied Superconductivity **3** 3043-3048.
9. C. Zuccaro, I. Ghosh, K. Urban, N. Klein, S. Penn and N.McN. Alford 1997 IEEE Transactions on Applied Superconductivity **7** 3715-3718.
10. T. Shimizu and Y. Kobayashi 2002 Proceedings on 4th topical symposium on millimeter waves TSMMW2002 191-194.
11. D. Kajfez 2001 Journal of the European Ceramic Society **21** 2663-2667.
12. Y. Kobayashi, Y. Kogami and M. Katoh 1993 Proceedings on 23rd European Microwave Conference, 562-563.
13. M. V. Jacob, J. Mazierska and J. Krupka 2003 (Under review in Superconductor Science and Technology).

(Received October 11, 2003; Accepted March 10, 2004)