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To cite this article: A Gensbittel et al 2008 J. Phys.: Conf. Ser. 97 012083

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MOCVD-SrTiO$_3$ Thin Film Microwave Coplanar Tunable Devices: Modelling of Varactors

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Abstract. SrTiO$_3$ (STO) ferroelectric (FE) thin films associated with High Temperature Superconductor (HTSC) is a good compromise to realize electronically tunable microwave devices combining tunable dielectric properties of FE films with low loss microwave conductivity in HTSC. STO, which exhibits a perovskite structure, is suitable for epitaxial growth of YBaCuO films and has been widely studied to realize tunable components around 77 K. Up to now, STO thin films were essentially deposited by sputtering and pulsed laser deposition. In the framework of this study, we have explored the feasibility of microwave devices made from STO thin films prepared by metalorganic chemical vapour deposition (MOCVD). We have characterized Au/STO(250 nm thick)/MgO coplanar waveguide transmission lines and microwave variable capacitors (varactors) from 45 MHz up to 40 GHz, in the 300 K to 60 K temperature range. Dielectric characteristics of the STO films were extracted from measurements and studied as a function of frequency, electric field and temperature. The geometry of the interdigital capacitors (IDC) was chosen after evaluating their capacitances using an analytical theoretical model. We have used a deEmbedding method to extract, from electromagnetic simulations using Sonnet® Software, the capacitance of the IDC alone.

1. Introduction
Recently, thin films of ferroelectric (FE) materials have been extensively studied [1] as promising candidates for frequency-agile microwave circuit applications such as phase shifters, steerable array antennas, capacitors or filters. The voltage control of dielectric permittivity of high quality FE thin films, deposited on low loss dielectric substrates, allows to obtain faster tunable components, more compact and lightweight as compared as classical tuning systems such as mechanically tuned resonant structures, ferrite based components or semiconductor-based voltage controlled electronics [2].

SrTiO$_3$ (STO) FE thin films associated with high temperature superconducting (HTSC) materials is a good compromise to realize electronically tunable devices [3] combining controllable dielectric properties of FE films with low loss microwave conductivity in HTSC. STO, which exhibits a perovskite structure, is suitable for epitaxial growth of YBaCuO films and has been widely studied to realize tunable components around 77 K [4]. Up to now, STO thin films were essentially deposited by sputtering and pulsed laser deposition.

In the framework of this study, we have explored the feasibility of tunable microwave devices made from STO thin films prepared by metalorganic chemical vapour deposition (MOCVD) [5]. We have characterized Au/STO/MgO coplanar waveguide (CPW) transmission lines from 500 MHz up to
40 GHz, in the 300 K to 60 K temperature range. DC voltages from 0 to 60 V were applied to the devices to study their tunability. Dielectric characteristics on the STO thin film were extracted from these results. Then, microwave variable capacitors (varactors) were modelled and simulated. We have used a de-embedding method to extract, from simulations, the capacitance of the IDC alone.

2. Experimental
STO thin films were produced by an innovative MOCVD technique, called injection MOCVD [5]. 250 nm thick films were deposited on MgO single-crystals substrates. θ-2θ X-ray diffraction pattern for STO films indicated c-axis oriented structures.

CPW transmission lines of $l = 1.84\,\text{mm}$ length and of various widths (from 5 to 20 µm), and interdigital capacitors, whose geometry will be detailed in section 3, were designed. The CPW structures were patterned on the STO films through a lift-off mask by e-beam evaporation of 1 µm thick Au film.

The devices were characterized in a low-temperature probing station using a helium flow cryostat in the 300 to 60 K range. For contacting samples, a pair of commercial microwave coplanar probes (Picoprobe®) was used. $S$ parameter measurements were performed with a HP8510C (Agilent Technologies™) network analyzer in the 500 MHz to 35 GHz range. A SOLT (Short-Open-Load-Thru) calibration was performed at measurement temperature with a Cascade Microtech™ LRM (Line-Reflect-Match) calibration set. An external DC voltage bias up to 60 V could be applied through the coplanar probes, between the CPW centre line and the ground planes using internal bias T.

3. Dielectric properties extraction and varactor modelling

3.1. Dielectric permittivity and loss tangent of STO thin films
First, coplanar waveguide (CPW) transmission lines were realized on STO films. From $S$ parameter measurements performed on transmission lines, we have determined the complex propagation constant $\gamma = \alpha + j\beta$ using $S$ matrix converted to the transmission matrix (ABCD). From $\beta$, the effective dielectric constant $\varepsilon_{\text{eff}}$ of the CPW and then the dielectric permittivity $\varepsilon_{\text{STO}}$ of the STO thin film were extracted using the Gevorgian model [6] based on the conformal mapping technique. From $\alpha$, the effective loss tangent $\tan\delta_{\text{eff}}$ and then the loss tangent $\tan\delta_{\text{STO}}$ of the STO thin film were extracted using an other model [7], derived from the previous one [6].

3.2. Varactor modeling
Secondly, using these dielectric values at different applied electric fields, we designed interdigital capacitors (IDC) as illustrated on Figure 1 (c) and (d). The capacitance of the structures was calculated using the IDC model of Gevorgian [8]. We studied the tunability of the IDC using equation (1):

$$\Delta C_{\text{rel}}(\%) = \frac{C_{\text{0V}} - C_{\text{Vappl}}}{C_{\text{0V}}} \times 100,$$

with $C_{\text{0V}}$ and $C_{\text{Vappl}}$ the values of capacitance respectively without bias and with an applied voltage $V_{\text{appl}}$. Figure 2 shows the evolution of the calculated capacitance value and tunability as a function of different geometrical parameters (listed on Figure 1(d)): finger width $f_w$, gap between the fingers $f_g$, finger length $f_l$ and the number of fingers $n$. The geometry was chosen to obtain capacitance values not less than 1 pF, a tunability higher than 5 % and dimensions greater than 5 µm to keep a good accuracy with the used lithography techniques.

4. De-embedding technique for IDC
In microwave measurements, it is important to take accurately into account the parasitic elements. Indeed, the measured $S$-parameters contain the characteristics of the probing pads and of the lines connected to the device under test (DUT). A schematic of the global equivalent circuit containing a
DUT is shown on figure 3. We used a de-embedding method [9] to extract the capacitance $C_{DUT}$ of the DUT alone.

\begin{equation}
C_{deemb} = C_{DUT} = \frac{1}{2\pi f} \times \text{Im} \left( \frac{Y_{12DUT} \times Y_{12Thru}}{Y_{12DUT} - Y_{12Thru}} \right)
\end{equation}

The admittance $Y$-parameters were calculated using standard conversion equations from the measured $S$-parameters.

**Figure 1.** Schematics of devices for the de-embedding technique: (a) open circuit (b) transmission line (thru) (c) IDC (device under test DUT) and (d) detailed view of the capacitor.

**Figure 2.** Evolution of (a) the capacitance and (b) the tunability as a function of the finger width ($f_w$) for different values of the gap width ($f_g$) for an IDC with $n=20$ fingers of 1 mm length.

To determine all the unknown parameters (parallel admittances $y_i$ and series impedances $z_i$ as illustrated in figure 3), three test structures were characterized: Open, Thru and DUT shown in Figure 1. The first step began by subtracting out the $y_i$ parameters, obtained by Open structure characterization, from the experimental data of the DUT. In the second step, $z_i$ elements, extracted from Thru structure measurements, were also subtracted. Finally, the capacitance $C_{deemb}$ of the DUT alone was given by equation (2).
To observe the efficiency of this de-embedding technique, the value of the capacitance $C_{dir}$ was also directly extracted from the transmission admittance parameter $Y_{12DUT}$ using equation (3) and was compared with $C_{DUT}$.

$$C_{dir} = \frac{-1}{2\pi f \text{Im}(Y_{12DUT})}$$  \hspace{1cm} (3)

![Equivalent circuit representation of the parasitic elements around the device under test (DUT).](image)

Figure 3. Equivalent circuit representation of the parasitic elements around the device under test (DUT).

5. Results

5.1. Dielectric properties of STO thin films

From transmission line measurements, the dielectric permittivity $\varepsilon_{STO}$ and the loss tangent $\tan \delta_{STO}$ of the STO films were extracted and studied as a function of frequency, temperature and applied voltage. Figure 4 shows the evolutions of $\varepsilon_{STO}$ and $\tan \delta_{STO}$ as a function of applied voltage at 10 GHz and 60 K. The relative variations of each parameter $\Delta\varepsilon_{STO}$ and $\Delta\tan \delta_{STO}$, calculated as $\Delta C_{rel}$ with equation (1), are respectively 26.8% and 50.6% for 30 V of applied voltage, corresponding to an electric field of 8.6 V/µm. We obtained a symmetric evolution for positive and negative voltages: at 60 K, the material is in the paraelectric state (i.e. above its Curie temperature $T_C$).

Both $\varepsilon_{STO}$ and $\tan \delta_{STO}$ decrease with increasing frequency. $\varepsilon_{STO}$ reaches values of 173 at 5 GHz, 151.6 at 10 GHz and 138 at 20 GHz. $\tan \delta_{STO}$ shows values of 0.13 at 5 GHz, 0.088 at 10 GHz and 0.8 at 20 GHz. We also studied the evolution of these dielectric parameters with the temperature. The electric field dependence of $\varepsilon_{STO}$ and $\tan \delta_{STO}$ is more important at low temperature and decreases for higher temperature to reach values less than 5% at 300 K.

![Variation of the dielectric permittivity (open squares) and of the loss tangent (full circles) of a STO film as a function of applied voltage at 10 GHz and 60 K. The relative variations between 0 and 30 V are given in percent.](image)

Figure 4. Variation of the dielectric permittivity (open squares) and of the loss tangent (full circles) of a STO film as a function of applied voltage at 10 GHz and 60 K. The relative variations between 0 and 30 V are given in percent.
5.2. Electromagnetic simulations of varactors

Electromagnetic simulations of IDC geometries were performed using Sonnet® software. Therefore, theoretical calculations, simulations and experimental results data could be compared.

Figure 5 shows the comparison between the capacitance values $C_{dir}$ and $C_{deemb}$ of an IDC extracted directly from the Sonnet® simulation and from this simulation using the de-embedding method respectively. On the zoom of the figure 5 (b), a solid line indicates the value of the capacitance given by the IDC Gevorgian model. We can clearly see in this figure, that the capacitance $C_{dir}$ shows a resonance around 4.5 GHz and is negative above. The de-embedding method allows to obtain the value of the IDC capacitance $C_{deemb}$ without any resonance for frequencies up to 10 GHz. This value is comparable to the value calculated using the IDC Gevorgian model [8]. Above 10 GHz, $C_{deemb}$ also presents successive resonances.

The de-embedding technique used allows to remove the big resonance at 4.5 GHz that can be due to parasitic elements around the IDC alone and to the association of the different impedances, admittances and capacitances of the global device containing the IDC (see Figure 1 (c)). But in the de-embedding capacitance, resonances are still observed because of the inductive part of the IDC. In fact, this de-embedding technique extracts the imaginary part of the admittance of the DUT alone that contains capacitance but also inductance parts of the device. We should study another theoretical model to identify the inductance values of the IDC fingers.

For IDC with shorter fingers, $C_{deemb}$ includes resonances but at higher frequencies. In the literature, Kim and al. [10] used this de-embedding technique for very short fingers and did not observe any resonance but fund much lower values of capacitances.

![Graph](image)

**Figure 5.** Evolution of the capacitances $C_{dir}$ and $C_{deemb}$ (see text) as a function of frequency for an IDC with $f_w = 20 \mu m$, $f_g = 10 \mu m$, $f_l = 1 mm$ and $n = 20$ digits. Figure 5 (b) shows a zoom of the graph of Figure 5(a). The solid line shows the value of the capacitance given by the Gevorgian model.

The simulations were performed using values of $\varepsilon_{STO}$ and $\tan\delta_{STO}$ corresponding to different electric field values. The de-embedding capacitances are presented in Figure 6. We can see that $C_{deemb}$ increases with frequency and decreases with an applied electric field. A variable capacitor or varactor is so obtained. The relative variation of the capacitance of the IDC is around 10 % on the whole frequency range. It is very closed to the value estimated with the model [8] in section 3.
6. Conclusion
In summary, we have patterned and characterized Au/MOCVD-STO/MgO CPW transmission lines from 500 MHz up to 35 GHz, in the 300 K to 60 K temperature range. Dielectric permittivity and loss tangent of the STO thin films were extracted from measurements. We obtained at 10 GHz and 60 K, 27 % and 50.6 % of variation for respectively the dielectric permittivity and the loss tangent of the STO film for 30 V applied voltage, i.e. an applied electric field of 8.6 V/µm.

Then, we studied interdigital capacitors (IDC). Their geometry was chosen after evaluating their capacitances using an analytical theoretical model. We have used a de-embedding method to extract, from the electromagnetic simulations using Sonnet® software, the capacitance of the IDC alone. This technique allowed us to remove parasitic resonances from the direct characterization of the capacitors up to 10 GHz. Above 10 GHz, resonances appeared. They could be due to the inductance of the IDC fingers. A theoretical model could be used to identify this inductance. Simulations of the varactors showed a variable capacitance of the structures of 10 % between 0 and 8.6 V/µm.

Acknowledgements
The authors thank warmly F. Weiss (L.M.G.P. BP 257- INP Grenoble Minatec - 3 parvis Louis Néel - 38016 Grenoble) for the STO thin film deposition and Pr Paul Crozat (I.E.F., bât. 220/221, Université Paris-Sud 91405 ORSAY Cedex) for making available his microwave characterization setup. All the devices were patterned at the CTU (clean-rooms of I.E.F. in Orsay sponsored by the Conseil Général de l’Essonne).

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