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Analytical modeling method of thermal spreading resistance in BAW filters

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Abstract— **As the power requirements in BAW filters steadily increase, thermal behaviour emerges as a key asset to ensure device performance and reliability. Under these conditions, self-heating mechanisms drive to possible situations where the filters no longer meet the electrical specifications. In addition to that, the evaluation of the heat spreading might help to define the resonators and pillars distribution along with the overall performance of current BAW filters. In the past, numerical methods based on FEM have been used to study the temperature distribution under high-power (HP) signals, lacking efficiency in terms of computational time. The motivation of this work is to describe an analytical method that is able to simulate very fast, without the need of costly FEM simulation, the heat spreading in a filter according to the spatial distribution of the resonators.**

Keywords—BAW filters, analytical model, thermal network, power dissipation, self-heating, resonator, high power

I. INTRODUCTION

Microwave acoustic filters (SAW, BAW) are important components in today's RF front-ends and they are becoming key devices for the next generation of RF communications systems due to their compactness and high selectivity. One of the main challenges that arises for the compact module design is the thermal management of the generated heat into the resonators to maintain device reliability and lifetime.

Investigating the thermal performance of BAW filters subjected to high-power (HP) levels is still a concern within the RF industry and academia [1]. Applying high power levels to a filter may lead to a temperature increase into the resonators because of the dissipated power. The dissipated power in each resonator may impact its own performance and the properties of nearby resonators and thus affecting the overall filter performance [2]. The issue of the heat spreading in BAW filters has received considerable attention as changes of the temperature may induce deviations on the material parameters producing a possible frequency shift of the passband [3], [4].

Several attempts have been made to model the thermal physics on BAW filters using 3-D FEM methods [5]. However, a major problem with this kind of analysis is the lack of efficiency in terms of computational time. Previous studies have reported multi-physics modelling for analysing the devices at HP levels [6]. Whilst some research has been carried out on thermal analysis, to date there has been little quantitative analysis of BAW filters response considering the frequency dependent dissipated power in the resonators and the eventual spatial distribution of the temperature.

This paper describes a fast analytical model that, for a given filter and layout design, calculates the dissipated power at each resonator, the heat spreading throughout the wafer and the filter response considering the temperature at each resonator.

The heat spreading method is detailed in Section II. This method allows to model the heat transfer between resonators which along with the generated heat in the resonator itself, due to the dissipated power, allows to accurately know the temperature at each point of the wafer. The heat spreading between resonators can then be modeled with a thermal resistance network.

In Section III, a temperature dependent Butterworth-Van Dyke (BVD) model is envisioned whose thermal parameters are obtained from impedance measurements of single resonators as a function of the temperature from 40 K up to 300 K.

In Section IV, the whole analytical model is outlined. The thermal resistance network that accounts for the heat spreading is connected with all the BVD resonators and the resulting circuit is simulated with a commercial circuit solver Keysight Advanced Design System (ADS) ®.

This simulation method allows to detect critical hot-spots at each frequency and take corrective actions if required. For example, a new arrangement of the resonators could be decided and simulated very fast without the need of additional FEM simulations.

II. HEAT SPREADING METHOD

The aim of this study is to develop a fast analytical method based on previous works [7], [8] for multi-layered structures aiming to be much faster than the conventional 3-D FEM analysis. This includes the modeling of the vertical heat propagation through the thin layers forming the electrodes and acoustic reflector, and the heat spreading occurring in the silicon layer.

A. Vertical heat propagation

Due to the small thickness of the layers conforming bottom electrode and acoustic reflector in comparison with the area of the resonators, we will assume that the heat propagates vertically towards the silicon. This latter statement has been carefully confirmed throughout Comsol Multiphysics® simulations (Fig. 1).

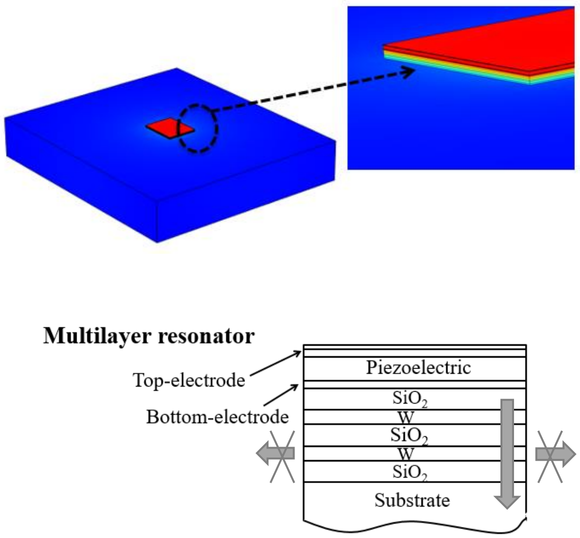

Fig. 1. Example stack configuration of multilayer resonator. Grey arrows represent considered heat propagation.

With this assumption, the vertical heat flux can be modeled with an equivalent thermal resistance following

$$R_i = \sum_{j}^{N_{layers}} \frac{t_j}{k_j A_i}, \qquad (1)$$

where k_j is the thermal conductivity of the layer j, t_j is its thickness and A_i is the area of the resonator [9].

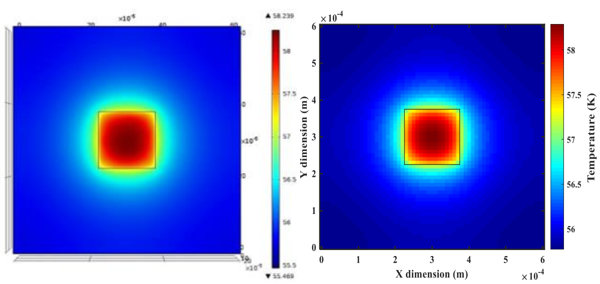

Fig. 2. Example of heat flow simulation of the silicon layer with a resonator acting as a heat source: Comsol results on the left, and Matlab results on the right. Legend represents the difference between the measurement temperature and the ambient temperature.

B. Heat propagation through the silicon layer and temperature distribution

This work considers that the heat generated into the lossy aluminum nitride (AlN) layer is spread in a semi-spherical manner at the silicon layer. That means that each resonator is considered as a finite rectangular flux channel with an eccentric heat source [7]. The temperature at any point is analytically calculated using Matlab® and a total thermal spreading resistance matrix $[R_{TS}]$ [7], [8] is finally obtained to relate the temperatures and the heat sources of all the resonators.

This method has been compared with the Comsol simulations for a single resonator (Fig. 2 left), providing differences in the temperature less than 1 % at any point in the same plane than the heat rectangular source.

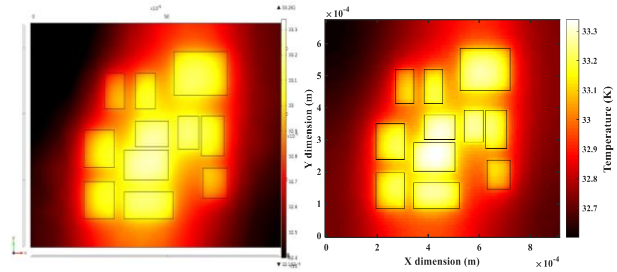

Fig. 3. Example of surface temperature distribution along the DIE area. Squares represent the resonators. On the left side Comsol simulations and the equivalent simulation with Matlab on the right.

In order to verify (1) and the stated approximations to calculate $[R_{TS}]$, Fig. 3 left shows an example of eleven in-plane heat sources, all of them with the same value, implemented with Comsol. The analytical proposed method (Fig. 3 right) agrees within 2% with the FEM simulations.

III. RESONATOR CHARACTERIZATION

The characterization is performed measuring several on-wafer resonators in a cryogenic probe station as a function of the temperature. The resonators are modeled using the BVD model, whose input parameters are temperature dependent. Figure 4 shows, as a function of temperature, the series resistance R_s, the static capacitance C_0 and the motional L_m, C_m, and R_m of a measured resonator. Any of these parameters can be modeled with a 2nd order polynomial given by

$$X(T) = X_0 + X_1 \Delta T + X_2 \Delta T^2, \qquad (2)$$

being $\Delta T = (T - T_{amb})$ the difference between the measurement temperature and the ambient temperature (T_{amb}=293.15 K).

IV. CIRCUIT MODEL AND FILTER EXAMPLE

A. Circuit model

The main goal is to obtain a circuital model for the heat propagation coupled to the BVD model where the self-heating effects of the resonators are included. Figure 5 shows a schematic representation of the overall thermal network. On the top, the representation of the die area modeled with the total thermal spreading resistance matrix $[R_{TS}]$ and delivered to the commercial circuit solver as a *. SnP file, which is provided by the analytical procedure outlined in Section II. Besides, the layers of the resonator stack are modeled with a series resistance connected to the ports of the die following (1). The end of each series resistance, which are named with resonator labels, is connected to the corresponding resonator (see Fig. 5).

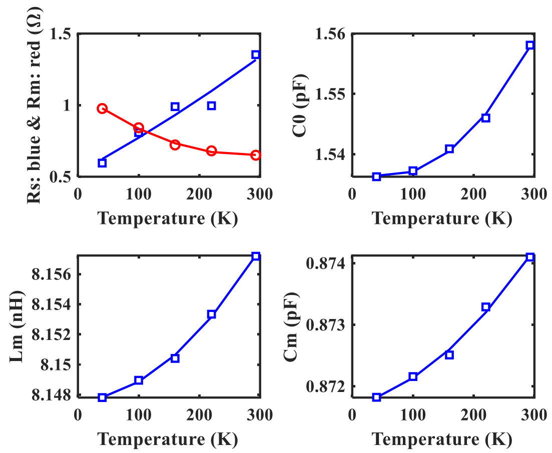

Fig. 4. BVD parameters adjustment as a function of temperature.

The lower part of Fig. 5 represents the filter topology where each resonator is modeled through its BVD model including one additional thermal port that is connected to the thermal network. The average dissipated power is calculated inside each resonator box and the generated heat is modeled with a DC current source flowing out through the thermal port.

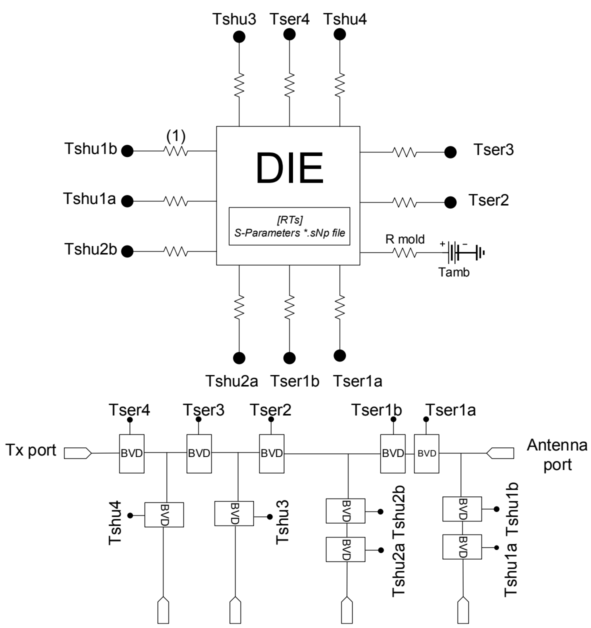

Fig. 5. Example thermal network of a BAW filter.

The thermal matrix interconnects all the resonators and accounts for the temperature at any resonator for specific heat sources, which are calculated from the losses dissipated according to the filter response at a given frequency. Then the temperature-dependent BVD resonators are updated to re-evaluate the response of the filter.

Note that the effect of the mold is also considered as a thermal resistance (R_{mold} in Fig. 5) connected to a DC voltage source which models the room temperature (T_{amb}). The value of the mold resistance is obtained once with Comsol and does not depend on the spatial distribution of the resonators within the die area. Therefore, is not necessary to perform more simulations unless the dimensions of the die changes.

Figure 6 represents a simplified cross-section of the packaged filter. The [R_{TS}] matrix is represented in this scheme with the *Rsil* resistances that interconnect two resonators and the package. Each stack material is simplified using a resistance (R_i in Fig. 6) in the analytical model. On the other hand, the effect of the package (R_{pack}) and the laminate (R_{lam}) are both included in the resistance R_{mold} of Fig. 5. Note that convection and radiation effects marked in red are neglected.

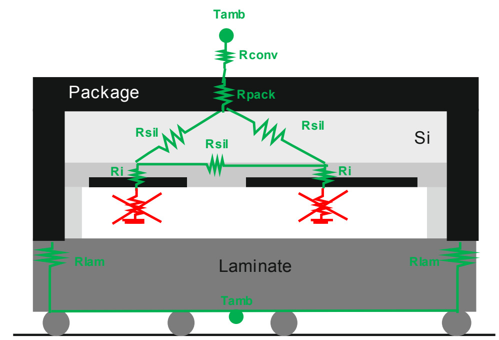

Fig. 6. Simplified cross-section of the filter. Red resistance represent radiation and convection effects not considered.

B. Filter example

Once the filter is synthesized and the areas of the resonators are decided, a spatial distribution is proposed considering the die and the resonators, as depicted in Fig. 7.

In particular, an 8-order B7 duplexer T_x filter is used. Starting from the antenna port, the first element is a shunt resonator (Tshu1) followed by a series resonator (Tser1) and so on as indicated in Fig.5 bottom. Figure 7 shows the size and spatial distribution of the resonators. The anti-parallel connected resonators used to avoid 2nd harmonic nonlinearities are plotted in red squares in Fig 7. Those resonators are the ones closer to the antenna port (Fig. 5).

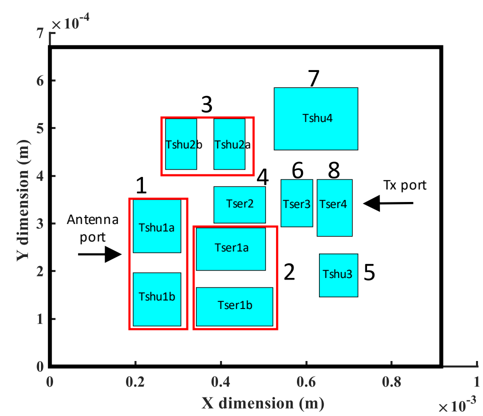

Fig. 7. Plot of the total die area of the proposed BAW filter. Blue squares represent active resonators of the spatial distribution.

The main objective is to assess the response degradation of the filter as a function of power where the self-heating effects are considered. Understanding and predicting the thermal effects gives control to optimize both resonators layout distribution of the filter at the design stage, and, also to avoid possible unwanted nonlinear behaviour. Figure 8 shows the simulated filter response, transmission and reflection, from 2.45 GHz to 2.65 GHz. Two different cases are considered, when the power is set to 0 dBm (dashed lines) and when the power is set to 30 dBm (solid lines). Results indicate a small up frequency shift of 1MHz. Effects on the reflection coefficient are more noticeable, indicating a variation on the matching filter performance.

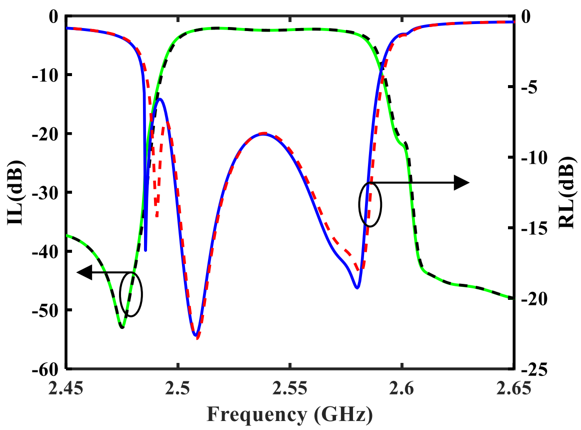

Fig. 8. Simulated passband response insertion loss (IL) of a BAW filter (green and black) and input return losses (RL) (red and blue traces).

Another key aspect is to evaluate the temperature of each resonator at HP levels. Figure 9 depicts the temperature rise for both series and shunt resonators at 30 dBm.

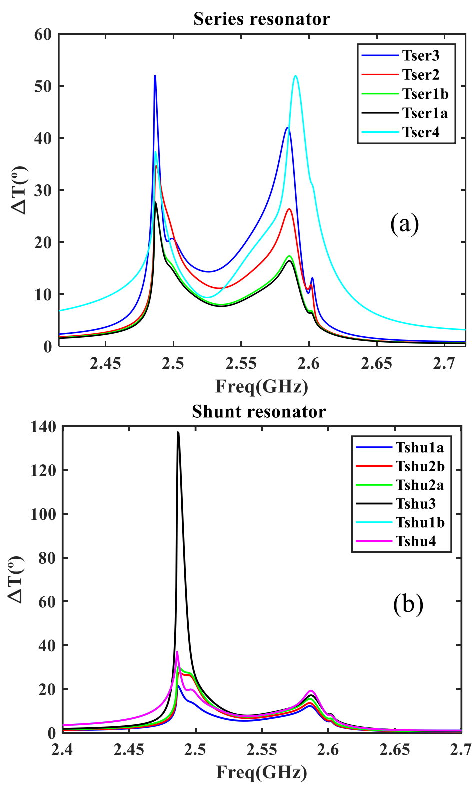

Fig. 9. Simulated resonator temperature dependence for series resonator (a) and shunt resonator (b). ΔT the difference between the simulated temperature and the ambient temperature.

In general, series resonators experience slightly higher temperatures than shunt resonators out of the filter passband. On the other hand, both series and shunt resonators reach the maximum temperature value at 2.490 GHz except for Tser4 resonator (cyan trace Fig. 9. (a)) at 2.590 GHz. Additionally, from Fig. 9 it is fairly clear that Tshu3 resonator (black trace Fig. 9. (b)) is the most critical, reaching a ΔT of 137 º at a given frequency.

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V. CONCLUSION

The proposed method uses a fast-analytical solution implemented with Matlab® for the heat spreading and temperature distribution inside the resonators. All the process is done under Matlab® without requiring costly FEM simulations. The accuracy of the developed analytical model simplification has been validated with Comsol step by step. The distortion on the filter response at HP signals is calculated allowing to modify resonator distribution for the filter to minimize the distortion at high power levels. Also, circuital simulations allow to identify critical resonators being possible to reallocate them and modify the initial design if needed to maintain the filter requirements.

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