Characterization of the Complex Permittivity of Thin Films Using a Slow-wave Coplanar Strips Resonator

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***Abstract*—This paper proposes a characterization method for the electromagnetic properties of thin films, based on the resonance properties of a slow-wave coplanar strips resonator. It is shown that using the resonant frequency and the quality factor of the resonator, permittivity and loss tangent of an unknown thin film at high frequencies such as mm-wave frequencies can be accurately determined. The method is validated by characterizing a silicon dioxide layer in an standard CMOS process as the thin film under test.**

I. Introduction

Characterization of thin films of dielectrics, especially for integrated circuit applications, is of great importance in microelectronics [1]. At microwave and mm-wave frequencies, characterization is usually based on transmission lines (TLs), in contrast to parallel plate capacitors used at low frequencies [2], [3] . The main limitation of the TL method is that extremely thin film layers, as encountered in integrated circuit technologies, results in too low characteristic impedance in microstrip lines, and are not sufficient to provide mechanical support for coplanar structures. Recently, Franc et. al. [4] proposed adding a thick layer of an already known material underneath the unknown thin film to provide the required mechanical support for coplanar waveguide technology. However, since adding a thick layer reduces the sensitivity, a patterned shielded coplanar waveguide was used to confine the electric field to the unknown thin film, resulting in an increased sensitivity to the thin film electromagnetic properties.

This paper proposes the characterization of both relative permittivity and conductivity of an unknown thin film using a slow-wave coplanar strips resonator. The proposed concept is demonstrated through simulation by characterizing a thin silicon dioxide layer in a CMOS process.

II. Proposed Method and Simulation Results

Figure 1 depicts the structure of the proposed slow-wave coplanar strips (S-CPS) for the characterization of the thin SiO_2 layer, which is sandwiched between the CPS and the floating strips. If the far end of the CPS is short-circuited a balanced resonator is realized. It is shown that resonant frequency and quality factor of the resonator can be used for determination of the complex permittivity of the sandwiched layer. In order to maximize the sensitivity of the thin film characterization the balanced resonator needs to have a high quality factor. To this end, based on the guide lines in [5] and [6], in order to reduce the resistive loss, the thick top metal layer is used for the implementation of the CPS. Furthermore, an array of very narrow floating strips are placed in the underlying metal layer to confine the electric field to the thin film under test and reduce the substrate conductive loss. In this structure the floating strips also reduce the resonator's length.

For the full-wave electromagnetic simulations, typical parameters and dimensions of a standard CMOS process, mentioned in the caption of Fig.1 is used. Metal layers thicknesses are $2.8\,\mu m$ for the CPS and $0.64\,\mu m$ for the array of floating

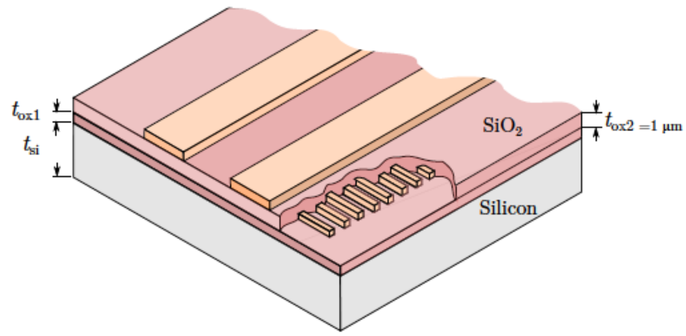

Fig. 1. Slow-wave coplanar strips with underlying floating strips in a CMOS process. The top SiO_2 layer is the thin film under test. For the full-wave EM simulations following parameters and dimensions are used: silicon substrate thickness, relative permittivity and resistivity are $t_{si} = 700\,\mu m$, $\epsilon_r = 11.9$ and $\rho = 10\,\Omega \cdot cm$, dielectric layers relative permittivity is $\epsilon_r = 3.8$ and their thicknesses are $t_{ox1} = 2.8\,\mu m$ and $t_{ox2} = 1\,\mu m$.

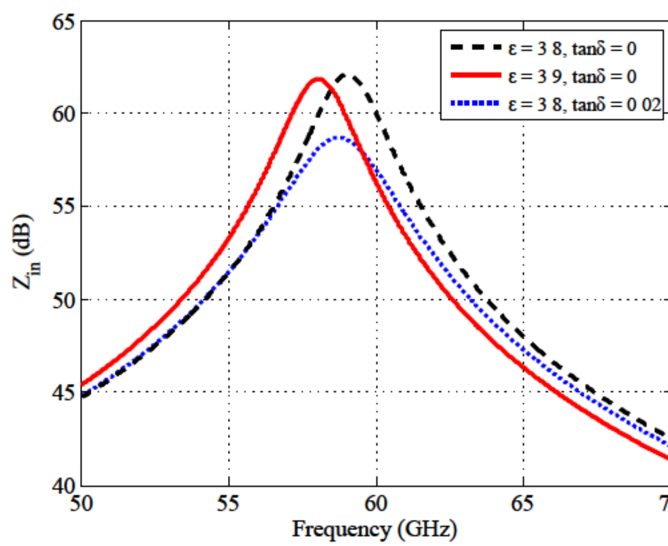

Fig. 2. Simulation results for normalized input impedance, demonstrating the variation of resonant frequency and quality factor of the resonator by small changes in the permittivity and conductivity of the thin film under test.

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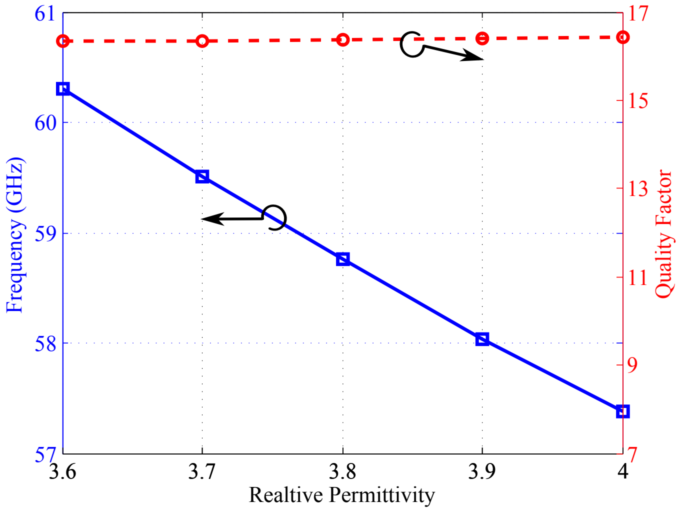

Fig. 3. Simulated resonant frequency and quality factor of the proposed slow-wave resonator versus relative permittivity of the thin film under test with $\tan(\delta) = 0.02$. Simulation results show that while an increase in the relative permittivity of the thin film under test effectively decreases the resonant frequency of the structure, it does not have a significant effect on the resonance quality factor.

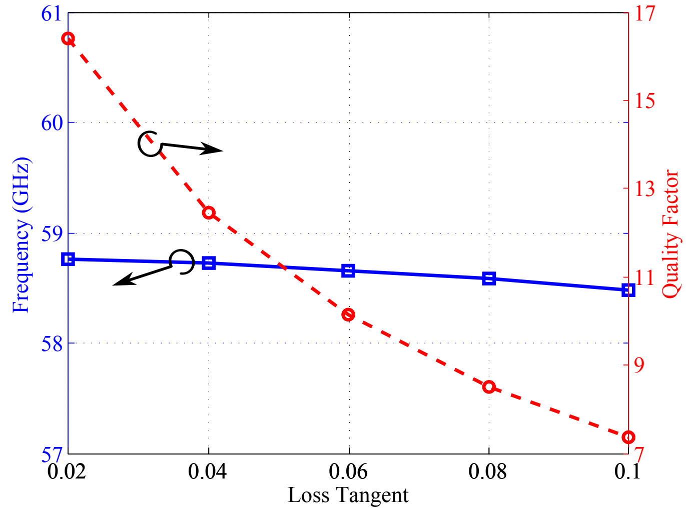

Fig. 4. Simulated resonant frequency and quality factor of the resonator versus the loss tangent of a thin film with $\epsilon_r = 3.8$. Simulation results show that quality factor of the resonator can be used for determining the conductivity of the thin film under test.

strips. The short circuited CPS resonator has a length of $230\,\mu\text{m}$, width $w = 25\,\mu\text{m}$ and spacing $s = 30\,\mu\text{m}$ and it is loaded with an array of floating strips with width $w_s = 0.6\,\mu\text{m}$ and spacing $s_s = 1.8\,\mu\text{m}$ to resonate at $59\,\text{GHz}$.

Figure 2 shows the simulated normalized (relative to 1 Ω) input impedance of the resonator. Comparing the simulated resonant frequency and quality factor of the resonator for a lossless thin film with $\epsilon_r = 3.8$ (black dashed line) to those of a lossless dielectric with $\epsilon_r = 3.9$ (red solid line) shows that since the electric field is mostly confined to the thin film under test, the resonant frequency of the structure is highly dependent on the permittivity of the thin film. Furthermore, the simulation results for a lossy thin film with $\epsilon_r = 3.8$ and $\tan\delta = 0.02$ (blue dot line) shows that while any change in the loss tangent of the thin film does not have a considerable effect on the resonant frequency, it effectively changes the quality factor of the resonator.

Figure 3 depicts the resonant frequency (blue solid line) and the quality factor (red dashed line) of the resonator versus relative permittivity of the thin film under test. The figure clearly shows that while the change in the thin film relative permittivity from $\epsilon_r = 3.6$ to $\epsilon_r = 4$ changes the resonant frequency from $f_0 = 60.4\,\text{GHz}$ to $f_0 = 57.5\,\text{GHz}$, the resonance quality factor is almost unchanged. Thus, the resonant frequency of the proposed slow-wave resonator can be used for the characterization of the relative permittivity of a thin film of an unknown dielectric.

In contrast to Fig. 3, effect of the thin film conductivity on the central frequency and quality factor of the proposed slow-wave resonator is depicted in Fig. 4. The figure clearly shows that while change in the loss tangent of the thin dielectric layer has very small effect on the resonance frequency of the structure, it effectively changes the quality factor of the resonance. Thus, the quality factor of the resonance can be used for the characterization of the thin film loss tangent $\tan\delta$.

III. Conclusion

Resonance properties of a slow-wave coplanar strips resonator has been used for electromagnetic characterization of thin films of dielectrics. It has been shown through simulation that the resonant frequency of the structure is proportional to the relative permittivity of the thin film, while its quality factor is a function of conductivity of the thin film. Thus, it is demonstrated that the resonant frequency and the quality factor of the resonator can be used for accurate determination of the complex permittivity of the thin film. Since the method exploits a balanced slow-wave CPS, the on-chip sensing structure is very compact and the measurement process benefits from higher immunity to the environment noise.

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