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Microwave Dielectric Properties of On-Chip Liquid Films

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***Abstract*—A microwave characterization method for on-chip liquid film dielectric property measurement is developed. Microstrip-line based on-chip test structures are fabricated to characterize the microwave dielectric properties of various on-chip liquid films: DI water and binary mixtures of DI water with glucose and ethanol. The obtained microwave dielectric properties are presented in Cole-Cole diagrams, which show general frequency dependence similar to that of bulk liquids. Different concentration levels of glucose and ethanol show different microwave dielectric responses. Therefore, on-chip microwave dielectric spectroscopy provides a promising and inexpensive on-chip sensing mechanism for biomedical and chemical applications.**

I. INTRODUCTION

Microwave dielectric spectroscopy, which measures the frequency responses of polarized molecules and charged molecules, has been one of the most reliable techniques for investigating bulk liquid dynamic relaxation and dynamic structures [1]. The method is also promising for on-line biomedical and chemical sensing due to its unique characteristics [2-4]: proteins and other biological molecules have rather large and distinct dielectric properties in microwave spectrum; the ionic contributions to the conductivity of water under most physiologically useful systems is greatly diminished. Furthermore, the rapid development of inexpensive integrated microwave systems in CMOS technology is expected to provide an ideal platform, such as the proposed network-analyzer-on-chip [5], for broad applications of this technology. The method may also be developed to provide lab-on-a-chip [6] a versatile, sensitive and selective scheme for analyte and process sensing with signal transduction capabilities. As a result, (analyte) liquids need to be incorporated with on-chip microwave sensing structures, such as Microstrip lines. One of the challenges therein is the microstrip-line based dielectric measurement methodology when standard silicon substrate in CMOS technology, instead of lossless glass substrate [2-4], is used.

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The incorporation of liquids on-chip is not only for convenience (such as system integration with less sample consumed), but also of necessity since many bio-chemical interaction processes involve liquid thin films and/or confined liquids, which have characteristics different from that of bulk liquids. The differences are caused by the confinement and surface interactions, such as surface tensions.

In this work, we report our preliminary results on microwave dielectric property characterization of on-chip liquid films, including DI water films, mixture films of DI water-with different concentration level of ethanol and glucose.

II. EXPERIMENTAL SET-UP AND DIELECTRIC PROPERTY EXTRACTION METHOD

A. On-Chip Microstrip Transmission Line Sensing Structures

Fig. 1 shows the measurement setup. The blue lines indicate aluminum transmission line structures. The yellow lines indicate walls, which was made out of photo resist, for liquid confinement. Special caution is needed when measuring ethanol related liquids.

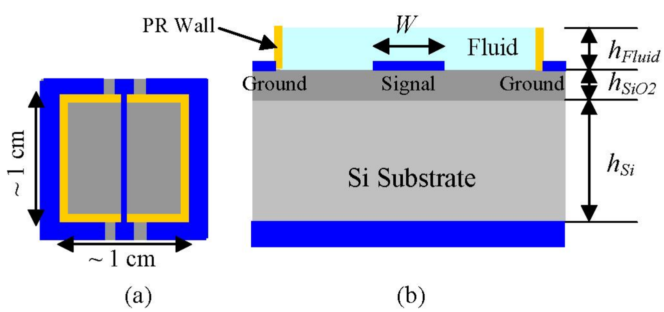

Fig. 1. Schematic of an on-chip microstrip transmission line. (a) Top view. (b) Cross-section view. Drawing not to scale.

B. Dielectric Properties Extraction Procedures

Fig. 2 is a generic equivalent circuit model of on-chip transmission line. Line parameters can be obtained through R = Re $\{\gamma Z\}$, G = Re $\{\gamma/Z\}$, L = Im $\{\gamma Z\}/\omega$, C = Im $\{\gamma/Z\}/\omega$, where γ (propagation constant) and Z (characteristic impedance of the transmission line) can be extracted from s-parameters [7].

There are multiple dielectric layers for the microstrip lines shown in Fig. 1. Assume quasi-TEM mode wave propagation and linear, homogenous and isotropic dielectric layer, then the

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effective dielectric constant, $\varepsilon_{eff} = \varepsilon_{eff}^{'} - j\varepsilon_{eff}^{''}$, can be expressed in terms of line parameters C and G.

$$\varepsilon_{eff}^{'} = C Z_0^{air} v_p \tag{1a}$$

$$\varepsilon_{eff}^{''} = \frac{G}{C\omega}\varepsilon_{eff}^{'} = G Z_0^{air} v_p / \omega \tag{1b}$$

Here C and G are the total line capacitance and conductance per unit length with the existence of multiple dielectric layers, respectively. Z_0^{air} is the impedance when replacing the dielectric layers by air. v_p is the phase velocity of light in vacuum. ω is the radian frequency.

Use the results of multilayer microstrip lines in [8], our narrow microstrip (w/h <<1) has

$$\varepsilon_{Fluid} = \frac{q_2(\varepsilon_{eq} q_1 - \varepsilon_{eff})}{(1 - q_1 - q_2)\cdot(\varepsilon_{eff} - \varepsilon_{eq} q_1) - (1 - q_1)^2} \tag{2}$$

Here q_1 and q_2 are filling factors evaluated from [8]. ε_{eq} is the equivalent dielectric constant of the double-dielectric-layer substrate. The capacitance of each layer is connected in series fashion and ε_{eq} is evaluated in [9].

III. Results and Discussions

Fig.3 shows the Cole-Cole diagram of the DI water at room temperature. ε' and ε'' are the real and the imaginary part of the dielectric constant, respectively, obtained by use of (1a) and (1b). Fig. 4 and Fig. 5 show the Cole-Cole diagrams for the water-ethanol and water-glucose mixtures, respectively. Their dielectric responses exhibit trends similar to that of their bulk counterparts [10]. But there are some obvious differences, including generally larger loss (ε''). Further work is needed to understand the discrepancies. The semicircle curve indicates a single relaxation time, and deviation from the semicircle implies a relaxation time distribution. The results also show that there are distinctively different dielectric properties for different liquids, including mixture liquids at different concentrations. The higher concentration level is, the smaller radius of the semicircle is, which indicates different molecular interaction.

Among the issues that need further exploration are: (i) to develop more accurate de-embedding procedures, such as the multi-line de-embedding procedure [11] even though the method requires larger chip areas; (ii) to develop more sensitive test structures. Current test-structures use only part of the electric fields; (iii) liquid confinement arrangement need to be further improved.

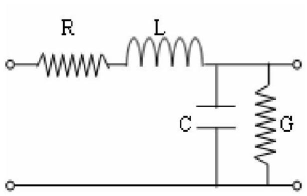

Fig. 2. A generic equivalent circuit model of on-chip transmission line.

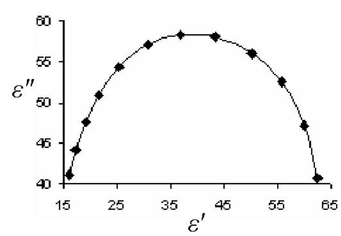

Fig. 3. Cole-Cole diagram for water at room temperature.

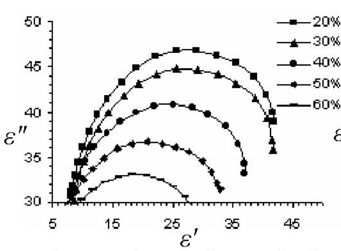

Fig. 3. Cole-Cole diagram for five mixtures of water-ethanol at room temperature.

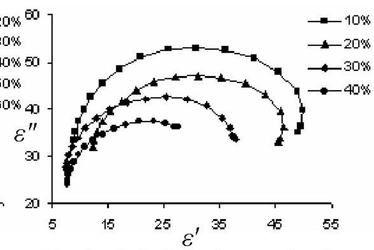

Fig. 4. Cole-Cole diagram for four mixtures of water-glucose at room temperature.

IV. Conclusions

The developed microwave characterization method works reasonably well for on-chip liquid film measurement. The obtained Cole-Cole diagrams of water film and mixture liquid films show similarity and differences with that of bulk liquids. Different liquid films exhibit different dielectric characteristics, which can be exploited for biomedical sensing and signal transduction applications. Further works are needed to address the measurement accuracy and to understand the observed dielectric properties that are different from bulk liquids.

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