Simulation of the Impedance Response of Thin Films As a Function of Film Conductivity and Thickness

Y. Jin[1], S. Kumar[1], R. A. Gerhardt[1]

[1]School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA, USA

Abstract

1. Introduction

The electrical properties of materials are important in many different applications. In microelectronics for example, films must perform as insulators, semiconductor or as conducting layers. In recent years, scanning probe methods are being extended to the nanometre scale range since accurate high spatial resolution measurements of electrical properties are of great interest [1-3]. However, quantifying the electrical properties using these techniques has been hampered by size and shape effects of the sample and the probing tips used [2]. In particular, the smallest tips can result in capacitance values lower than a few fF (femto Farad), which is lower than the measurement resolution [4] as previously pointed out [5]. The systematic numerical study on the effects of parameters such as electrode size, film and substrate thickness and film and substrate properties on the electrical measurements is essential for thin film science, nanoelectronics and biomedical diagnostic applications. An earlier version of this project was reported in the 2009 COMSOL conference [6].

2. Use of COMSOL MULTIPHYSICS®

Impedance measurements involve the polarization of materials under an applied alternating electric field. The potential/current is time varying and usually harmonic [7] The simulations were performed using the time harmonic-electric currents solver in the AC/DC Module of COMSOL Multiphysics® software. The objective was to solve Maxwell's equations for the time harmonic electric potential phasor for 2D cases. Figure 1 shows a schematic of the cross sectional view of the structures that were simulated for obtaining the impedance response of thin films [8].

3. Results

Table 1 shows the effects of electrode size and film thickness on capacitance. As the electrode size increases the accuracy of the simulation is improved. The difference in the capacitance calculated by the simulation and the capacitance calculated by a parallel plate capacitor formula can be quite small when the electrode size was 3000 µm (as low as 0.02 % for a film of 100 nm in thickness). However, as the film thickness increases, the electrical potential distribution near the electrodes expands more [8]. The difference between the two can be quite large when film thickness was 1000 nm (up to 95.7 % for a circular electrode of 3 µm in diameter).

Figure 2 shows electric potential distribution with respect to film conductivity. The electric potential distribution becomes more complicated in the case of a relatively more conducting film (= 10-1 S/m).

Figure 3 displays the comparison between FEA simulation and equivalent circuit fitting. When a dielectric film (= 10-13 S/m) is deposited on a conductive substrate, some current flow can be expected between the thin film and the substrate as shown above. Therefore, the dielectric responses of the thin film can be highly affected by the substrate. Other issues can also occur for more conducting films (not shown).

4. CONCLUSIONS

This work highlights some of the factors that become important when conducting electrical property measurements. Combined FEA simulations and equivalent circuit analysis can be used to obtain the correct interpretation of the electrical properties of micro/nanoscale structures.

Reference

REFERENCES
[1] O. Schneegans, P. Chrétien, F. Houzé, and R. Meyer, "Capacitance measurements on small parallel plate capacitors using nanoscale impedance microscopy," Appl. Phys. Lett., vol. 90, p. 043116, 2007.

[2] L. Fumagalli, D. Esteban-Ferrer, A. Cuervo, J. L. Carrascosa, and G. Gomila, "Label-free identification of single dielectric nanoparticles and viruses with ultraweak polarization forces," Nat. Mater., vol. 11, pp. 808-816, 2012.

[3] L. Fumagalli, G. Ferrari, M. Sampietro, and G. Gomila, "Quantitative Nanoscale Dielectric Microscopy of Single-Layer Supported Biomembranes," Nano Lett., vol. 9, pp. 1604-1608, 2009.

[4] G. Gramse, M. Kasper, L. Fumagalli, G. Gomila, P. Hinterdorfer, and F. Kienberger, "Calibrated complex impedance and permittivity measurements with scanning microwave microscopy," Nanotechnoogy, vol. 25, p. 145703, 2014.

[5] R.A. Gerhardt and S. Kumar, “Electrical characterization of thin films at the nanoscale,” 2009 Nanotech Conf. and Expo poster presentation (Houston, TX) pp 1–17, poster available for download at http://hdl.handle.net/1853/42107.

[6] S. Kumar and R.A. Gerhardt, “Numerical Study of the Electrical Properties of Insulating Thin Films Deposited on a Conductive Substrate,” Proc. 2009 COMSOL Multiphysics (Boston, MA, USA) pp 1-5.

[7] T. A. Davis, "Algorithm 832: UMFPACK V4.3---an unsymmetric-pattern multifrontal method," ACM Trans. Math. Softw., vol. 30, pp. 196-199, 2004.

[8] S. Kumar and R. A. Gerhardt, "Role of geometric parameters in electrical measurements of insulating thin films deposited on a conductive substrate," Meas. Sci. Technol., vol. 23, p. 035602, 2012.

Figures used in the abstract

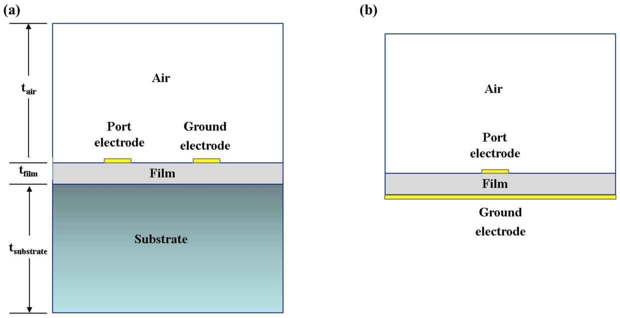
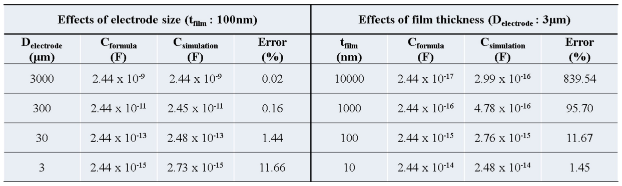


Figure 1: Figure 1. Schematic of the configuration for impedance modeling, (a) side view of the 2D (full) model, and (b) side view of the 2D (simplified) model in which the substrate is ignored. (Modified from ref. [8])



Effects of electrode size (t_{film} : 100nm)				Effects of film thickness ($D_{electrode}$: 3μm)			
$D_{electrode}$ (μm)	$C_{formula}$ (F)	$C_{simulation}$ (F)	Error (%)	t_{film} (nm)	$C_{formula}$ (F)	$C_{simulation}$ (F)	Error (%)
3000	2.44×10^{-9}	2.44×10^{-9}	0.02	10000	2.44×10^{-17}	2.99×10^{-16}	839.54
300	2.44×10^{-11}	2.45×10^{-11}	0.16	1000	2.44×10^{-16}	4.78×10^{-16}	95.70
30	2.44×10^{-13}	2.48×10^{-13}	1.44	100	2.44×10^{-15}	2.76×10^{-15}	11.67
3	2.44×10^{-15}	2.73×10^{-15}	11.66	10	2.44×10^{-14}	2.48×10^{-14}	1.45

Figure 2: Table 1. Comparison of capacitance of 2D calculations using different electrode sizes and film thicknesses.

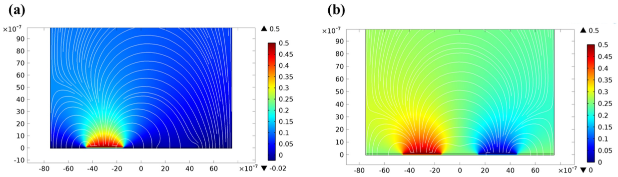


Figure 3: Figure 2. Film conductivity effects on the electric potential distribution when. (a) = 10-13 S/m, and (b) = 10-1 S/m at 1 Hz frequency respectively when using the full 2D model.

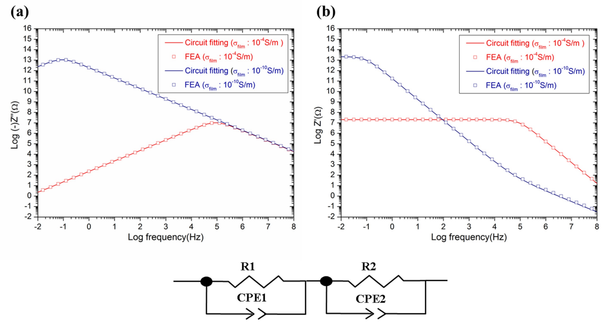


Figure 4: Figure 3. Bode plots for FEA 2D (full) model compared to equivalent circuit fitting. (a) Z' vs log f, and (b) Z" vs log f respectively for a film with thickness t= 100 nm.