Numerical Study of the Electrical Properties of Insulating Thin Films Deposited on a Conductive Substrate

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Introduction

- COMSOL Multiphysics was used to calculate the impedance/dielectric response of thin films attached to conducting substrates.
- In this presentation, we describe:
  - Models used
  - Effect of film thickness
  - Effect of electrode contact

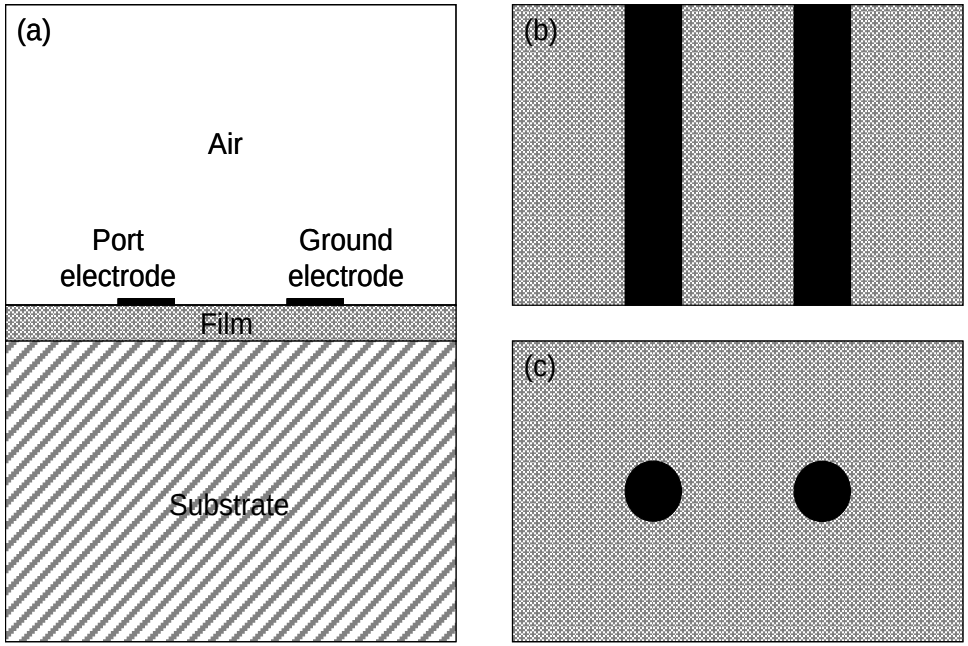
Important relationships

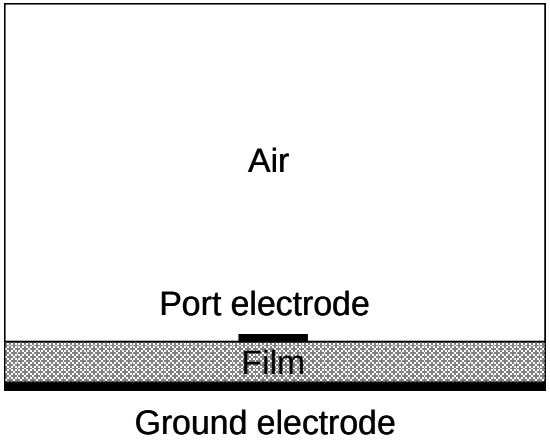
- Impedance Z = 1/Y = Z′ - j Z″
- Admittance Y = 1/Z = Y′ + j Y″
- Capacitance C = C′ + j C″ = (Y″+jY′)/ω
- Utilized Time Harmonic-Electric Current solver in the AC/DC module of COMSOL 3.4:

$$\nabla \cdot \left(\varepsilon - j\frac{\sigma}{\omega} \right) \dot{\nabla} \tilde{V} = \nabla \cdot \left(\tilde{\varepsilon} \nabla \tilde{V} \right) = 0$$

- To calculate the impedance and capacitance, one of the electrodes was made a port and the other was made a ground

Models Used

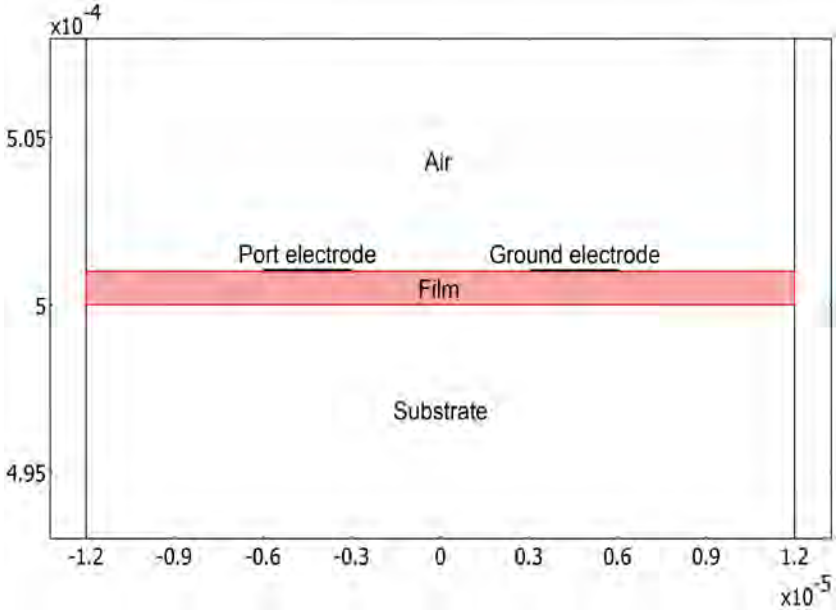




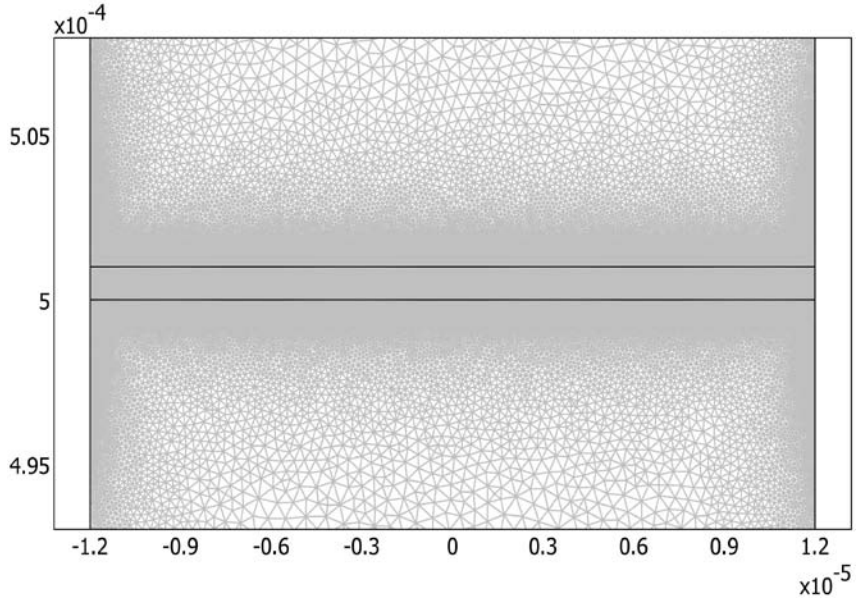
2D (full) model schematic

2D (simplified) model schematic

More details about the models



Typical 2D (full) model

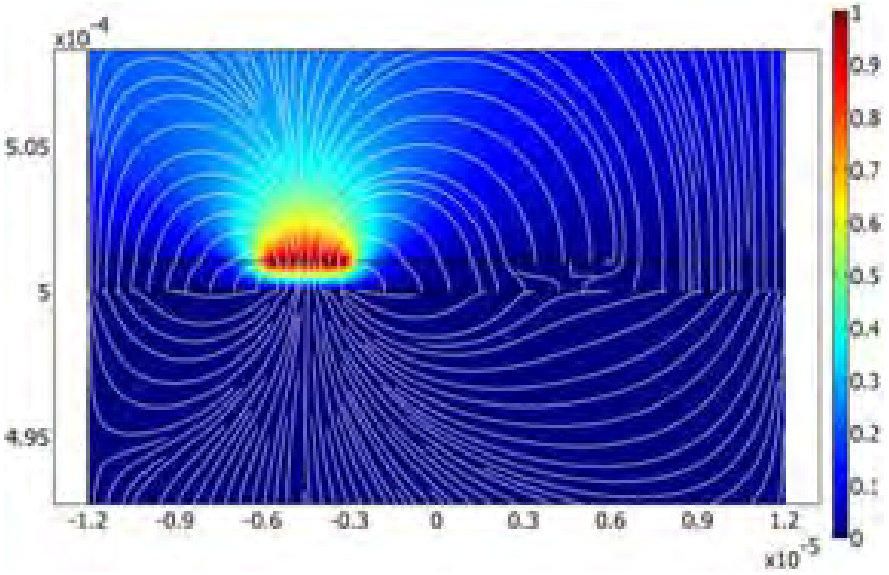


Typical 2D (full) mesh

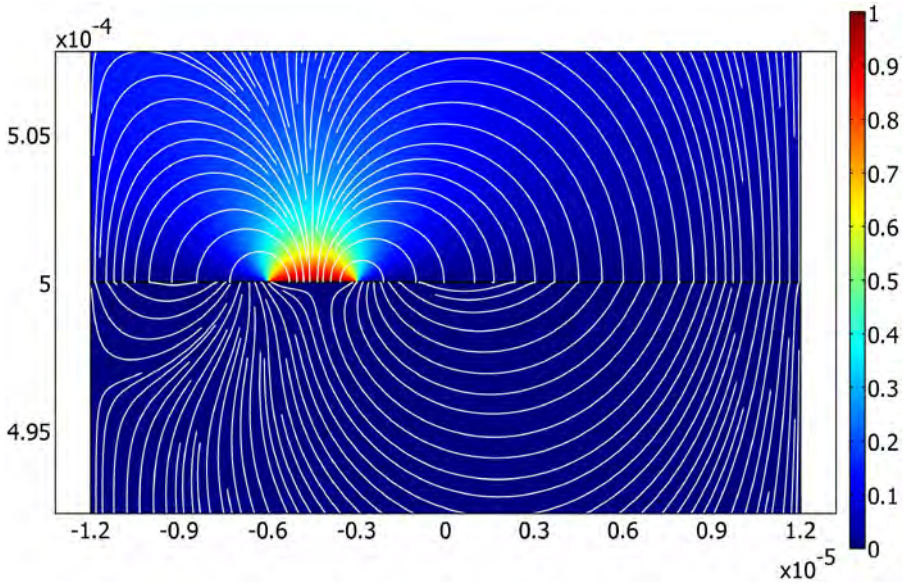
Evaluated Parameters

Model	t_{film} (nm)	σ_{film} (S/m)	$t_{substrate}$ (μm)	$\sigma_{substrate}$ (S/m)	$d_{electrode}$ (μm)
2D (full)	10, 50, 100, 500, 1000	10^{-13}	500	100	3
2D (simplified)	10, 50, 100, 500, 1000	10^{-13}	NA	NA	3
Axisymmetric (simplified)	100	10^{-13}	NA	NA	3, 30, 300

Results for two different film thicknesses

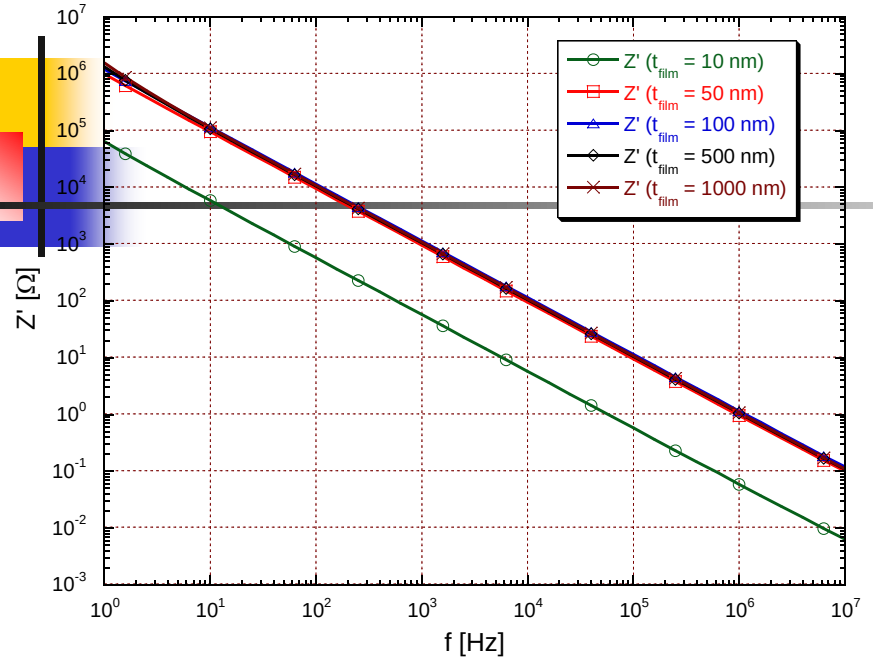


t = 1000 nm

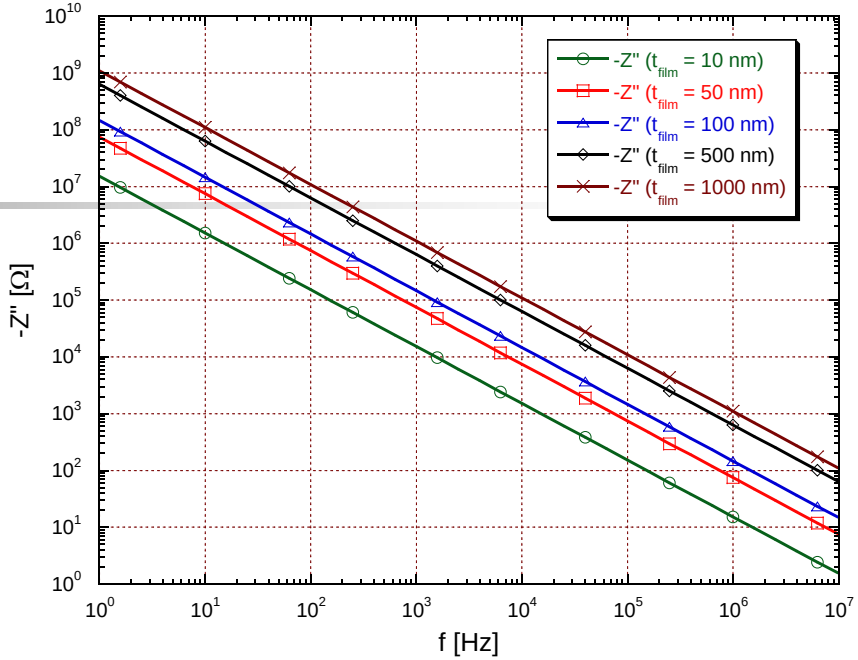


t = 10 nm

Effect of Film Thickness (Z) on Insulating Film

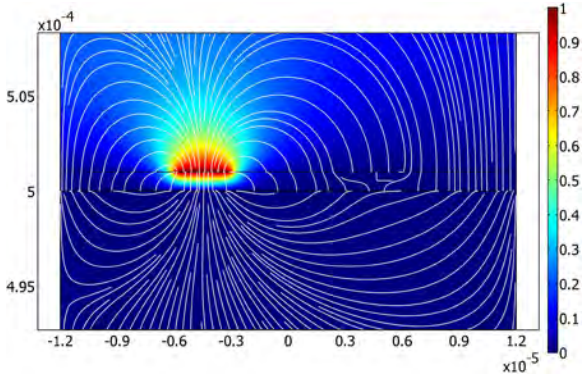


Bode plot of Z'

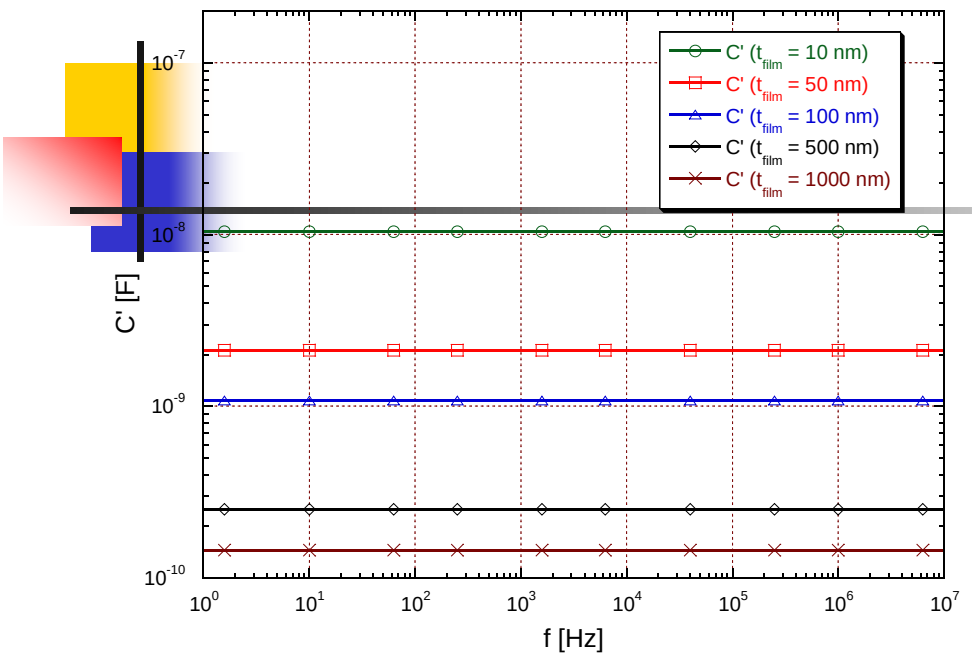


Bode plot of –Z"

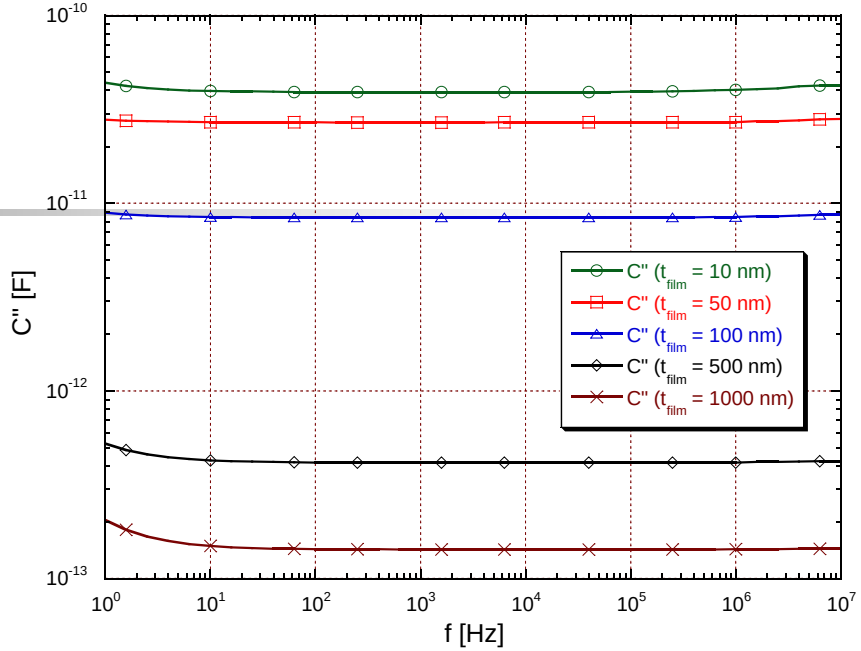
- Air thickness ~ 500 μm, air conductivity = $1x10^{-14}$ S/m.
- t_{film} = 10 to 1000 nm, σ_{film} = $1x10^{-13}$ S/m.
- t_{Si} = 500 μm, σ_{Si} = 100 S/m, $d_{electrode}$= 3 μm
- Z' does not change much.
- -Z" shows increasing trend with film thickness.



Effect of Film Thickness (C) on Insulating Film

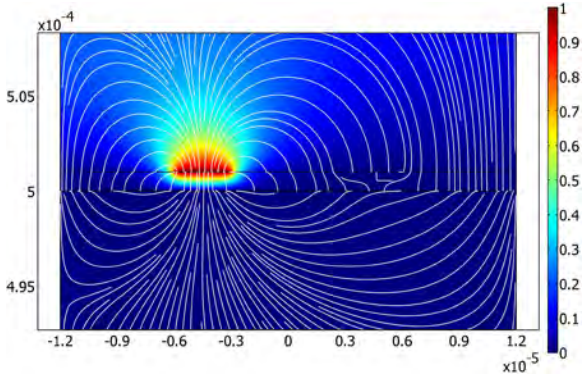


Bode plot of C'

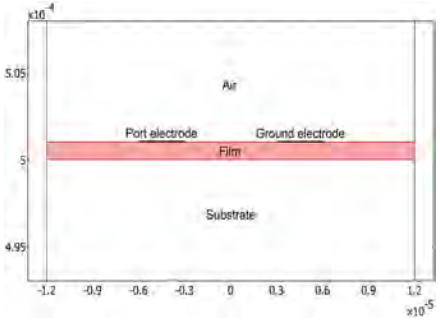


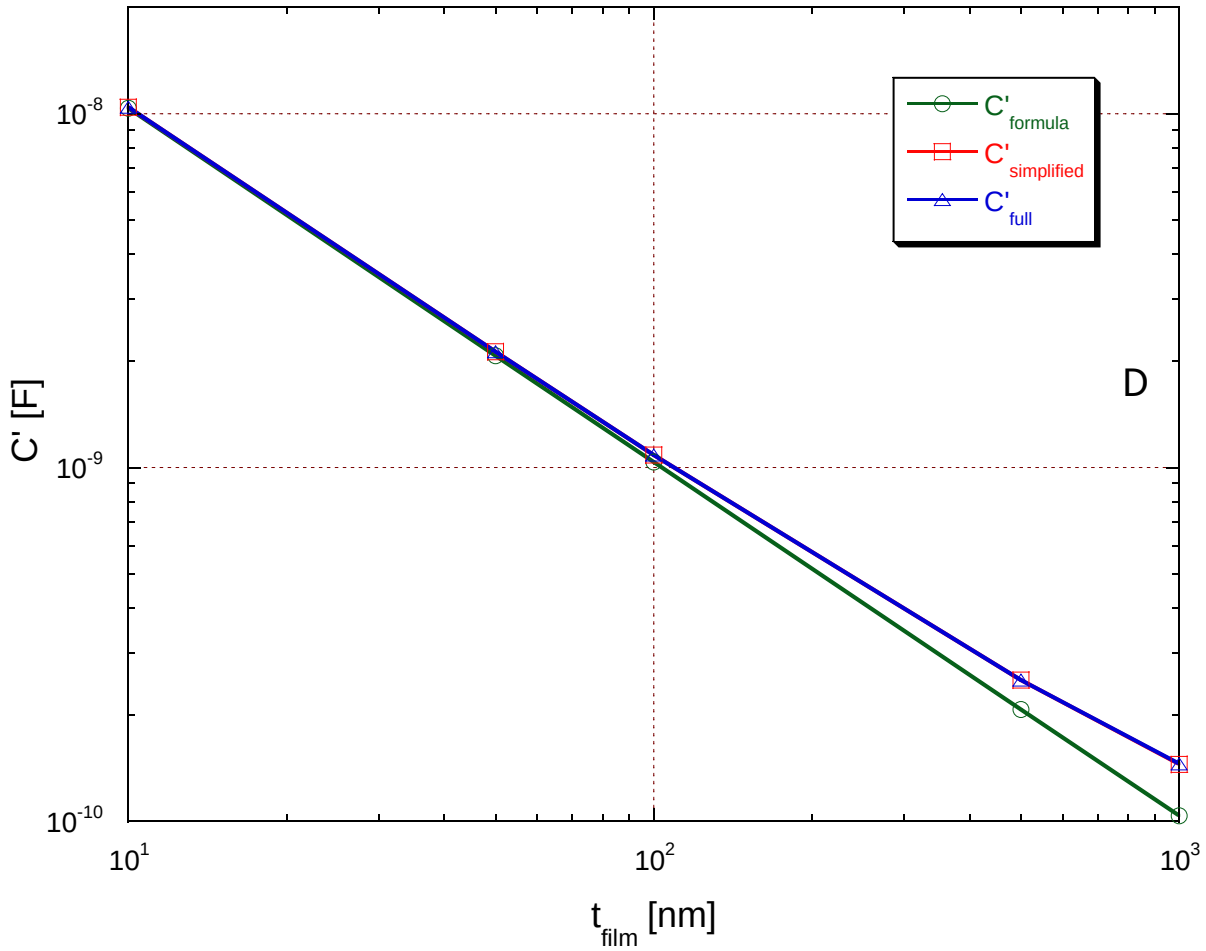
Bode plot of C"

- Air thickness ~ 500 μm, air conductivity = $1x10^{-14}$ S/m.
- t_{film} = 10-1000 nm, σ_{film} = $1x10^{-13}$ S/m.
- t_{Si} = 500 μm, σ_{Si} = 100 S/m, $d_{electrode}$= 3 μm
- C' shows decreasing trend with film thickness.
- C" also shows decreasing trend with film thickness, and curvatures are seen.

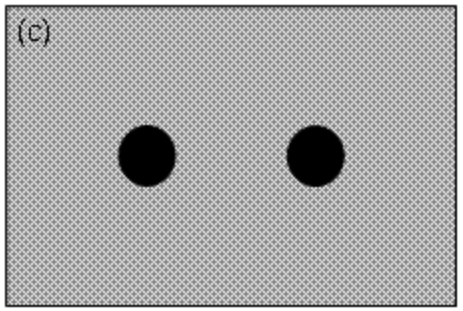


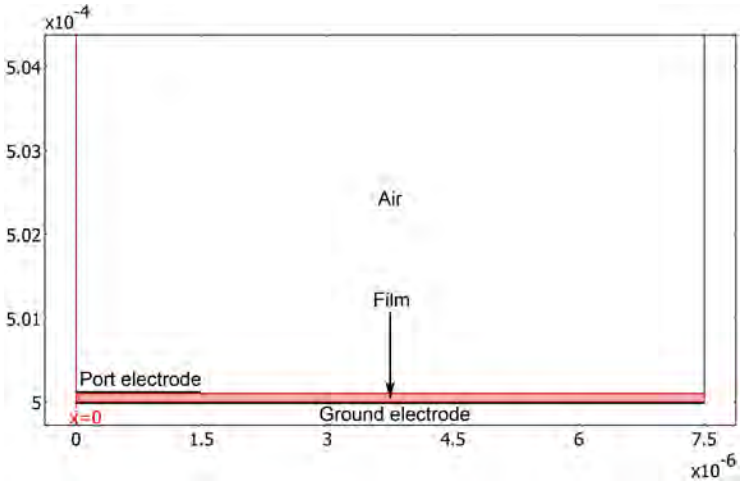
Comparison for the different linear models

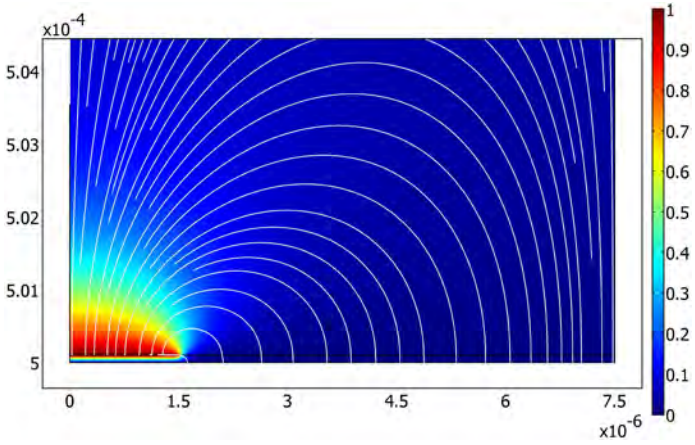




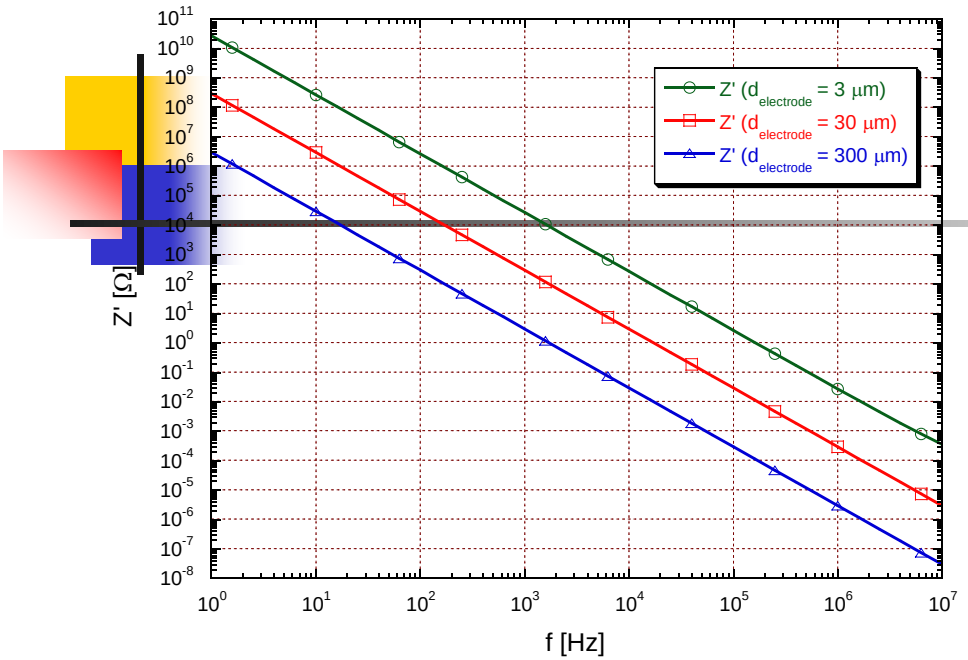
Axisymmetric Models



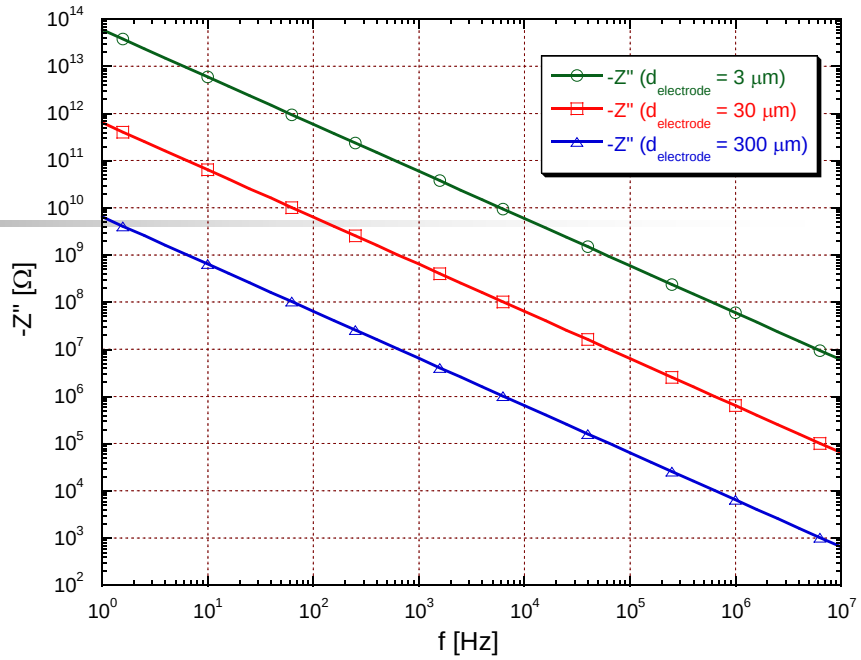




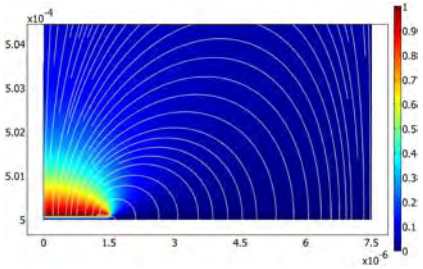
Effect of Electrode Size - Axisymmetric Models (Z)



Bode plot of Z'

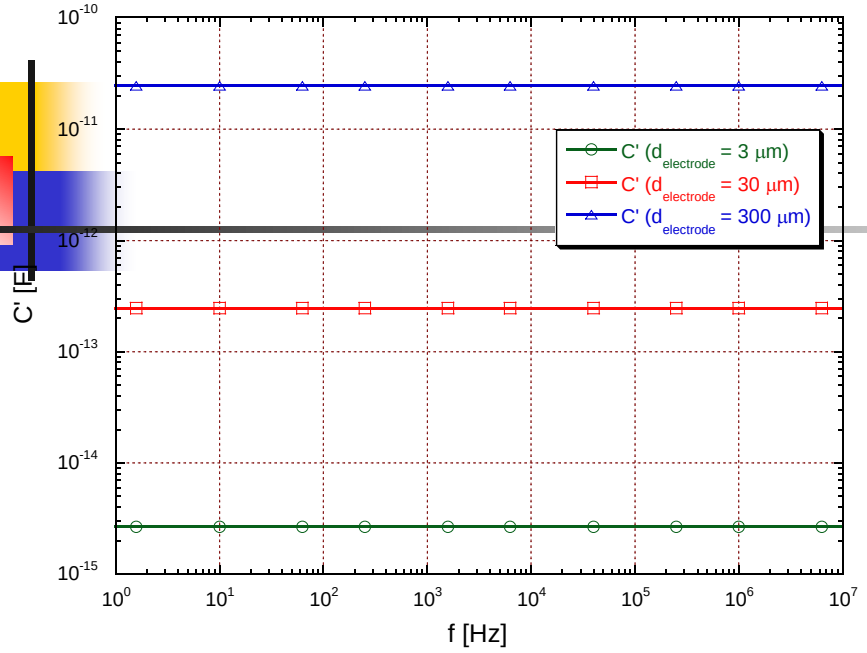


Bode plot of –Z"

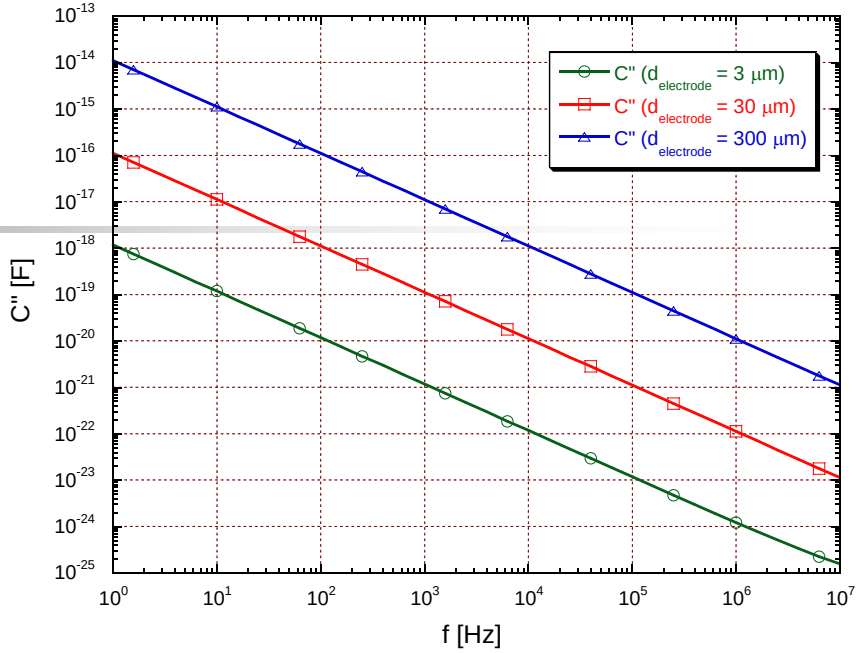


- Pad diameters, 3 μm, 30 μm, 300 μm.
- Air thickness ~ 500 μm, air conductivity = $1x10^{-14}$ S/m.
- Film thickness = 100 nm, film conductivity = $1x10^{-13}$ S/m.
- Si thickness = 0 um (Bottom electrode present).
- Impedance values do change as the size of the electrode is changed from small to large.

Effect of Electrode Size - Axisymmetric Models (C)

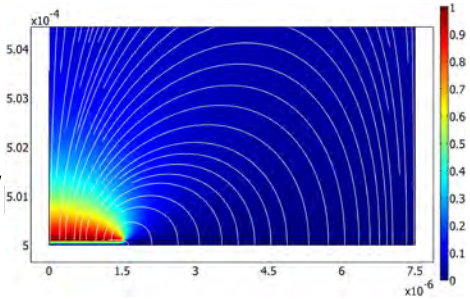


Bode plot of C'

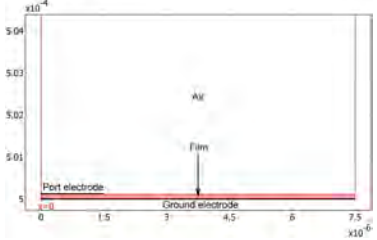


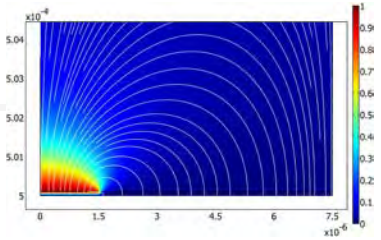
Bode plot of C"

- Pad diameters, 3 μm, 30 μm, 300 μm.
- Air thickness ~ 500 μm, air conductivity = $1x10^{-14}$ S/m.
- Film thickness = 100 nm, film conductivity = $1x10^{-13}$ S/
- Si thickness = 0 um (Bottom electrode present).
- Capacitance values almost the same as for simple parallel plate capacitor.



Electrode size effect





$d_{electrode}$ (μm)	$C'_{formula}$ (F)	$C'_{axisymmetric}$ (F)	$\left(\frac{C'_{simplified}-C'_{formula}}{C'_{formula}}\right)$ (%)
3000	2.441×10^{-9}	NA	NA
300	2.441×10^{-11}	2.444×10^{-11}	0.14
30	2.441×10^{-13}	2.468×10^{-13}	1.10
3	2.441×10^{-15}	2.656×10^{-15}	8.82

Conclusions

- Numerical simulations using COMSOL were used to model the electrical response of insulating thin films as a function of film thickness and electrode contact size
- The full and simplified models showed very little error when the films are very insulating

  ($\sigma_{film} \sim 10^{-13}$ S/m as for SiO_2) and the substrate is highly conductive ($\sigma_{Substrate} \sim 100$ S/m as for Si).
- The errors on the measured capacitance were shown to increase when the edge effects became dominant. This occurred as a function of increasing film thickness and as a function of decreasing electrode contact size as expected from ASTM D150 standards.

Acknowledgements

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