Effect of Thickness of an Insulating Material on Electrical Property Characterization and Edge Effects

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ABSTRACT

Silicon dioxide (SiO_2) thin films have various microelectronic applications because of the compound's insulating and dielectric properties. In characterizing the properties of thin films, it becomes crucial to take into consideration parameters such as thickness of the deposited material, homogeneity of the sample and its susceptibility to edge effects. If these features are not all accounted for, a drastically different electrical response may be seen from a thin film material, which will undermine the repeatability that is necessary to implement the material in a given application. For this study, the relationship of interest is the correlation between the thickness of deposited SiO_2 material and the role of edge effects in the impedance response of the sample. Other topics that will be discussed include the presence of defects or inhomogeneities and the effect of environmental factors on an insulating sample's electrical properties.

1 Introduction

Previous related work that has been done in the Gerhardt lab has focused on varying factors that affect the characterization of a thin film and then quantifying the electrical response of the material at the nanoscale level. This research has explored properties that affect the impedance response of a film, such as the composition of the film's substrate, the film's thickness and the size of the contacts used to make measurements on the surface of the film[1-4]. These factors must all be taken into account when measuring the impedance response, because they are all interdependent when it comes to electrically characterizing a material.

1.1 Varying Film Thickness

In 2009, the Gerhardt lab group published some initial work detailing the extent to which the thickness of a film's substrate affects the measured impedance response and capacitance of the film[1,2]. Using COMSOL Multiphysics® to simulate 2D configurations of SiO_2 films on a conducting Si substrate, the trend observed was that the real part of the impedance increased as the film's thickness increased but that its response was affected by the substrate thickness as well as properties[1]. Additionally, the simulations showed that when increasing film thickness, edge effects played a large role on the capacitance of the film[1,3]. Film thicknesses ranging from 10 to 1000 nm with a substrate Si thickness of 500 µm were inputted into the simulation, and the resulting impedance response was obtained. Two different models were evaluated, with one model taking the full details of the physical configuration while the other ignored the substrate and treated it as if it were the ground electrode[3,4]. It was found that the simplified model predicted behavior that agreed with the analytical impedance parallel plate configuration, which showed bigger edge effects for smaller contact electrodes or thicker films than would be predicted by ASTM D150[5]. These results are summarized in Tables 1 and 2 for 100nm films that would be measured with different sized electrodes and varying the film thickness on films while keeping the electrode size constant at 3µm respectively.

$D_{electrode}$ (µm)	$C_{formula}$ (F)	$C_{simplified}$ (F)	Error %
3000	2.441×10^{-9}	2.441×10^{-9}	0.016
300	2.441×10^{-11}	2.445×10^{-11}	0.164
30	2.441×10^{-13}	2.476×10^{-13}	1.442
3	2.441×10^{-15}	2.725×10^{-15}	11.655

Table 1. Effects of electrode size on 100nm film[3,4].

t_{film} (nm)	$C_{formula}$ (F)	$C_{simplified}$ (F)	Error %
10000	2.441×10^{-17}	2.993×10^{-16}	839.544
1000	2.441×10^{-16}	4.777×10^{-16}	95.697
100	2.441×10^{-15}	2.725×10^{-15}	11.665
10	2.441×10^{-14}	2.476×10^{-14}	1.447

Table 2. Effects of film thickness using 3 µm contacts[3,4]

1.2 Similar Trends observed for ZnO

In a study published by the Japanese Journal of Applied Physics, experimentation was performed on varying the thickness of zinc oxide (ZnO) films. ZnO is a semiconducting material and showed results similar to the simulation data discussed in the previous subsection. Five films of thicknesses between 1 Å (0.1 nm) and 24000 Å (2400 nm) were tested and graphed against the resistivity along with carrier concentration. A relationship that was determined through the data was that as the film thickness went up, the resistivity also increased due to its inverse relationship with the carrier concentration [6].

2. Experiments

In fall of 2014, a set of seven SiO_2 samples of different thicknesses fabricated via plasma-enhanced chemical vapor deposition (PECVD) were tested to experimentally determine the effect of the thickness on their impedance response. Using ellipsometry, the seven thicknesses of the samples were obtained and are shown in Table 3 below.

Sample Number	Thickness
1	9.76 nm
2	6.81 nm
3	12.07 nm
4	30.9 nm
5	64.89 nm
6	128.33 nm
7	352.99 nm

Table 3. Thicknesses of seven different samples of SiO_2.

The measured impedance response of the samples is shown in Figures 1 and 2. Measurements on these films were taken at the center of the samples which had been cut into quarters. The experimental setup included using a 4-point probe set up with probes that were 150 μm wide.

2.1 Varying Thickness Analysis

Upon completing experimentation, the samples showed much more error than expected based on the simulations. For one, the thin samples between 6.81 - 64.89 nm showed conductive behavior instead of the expected resistive behavior typical of SiO_2 thin films. This conductive electrical response could have been a result of several factors, including inhomogeneities within the samples, measurement probe contact with the Si substrate and the presence of environmental contaminants, which will be discussed later in the paper.

2.2 Edge Effects Experimentation

In the fall of 2015, the same SiO_2 samples were again taken and measured in order to conduct a separate edge effects analysis. Edge effects are known to play a role in the electrical characterization of materials, but the extent to which they affect the impedance response of an insulating material has not yet been quantified in current materials research. An anticipated result of this experimentation was that the presence of edge effects would have a large enough role to substantially change the resulting impedance response in a way that could be directly observable for samples of different thicknesses. The samples were measured with the same four-point probe technique mentioned in the previous section on thickness variation. For each sample, measurements were taken at three locations: 1) the center of the sample, 2) a location closer to the edge and 3) a location on the edge of the sample. The orientation of these measurements with respect to the sample is shown in Figure 3.

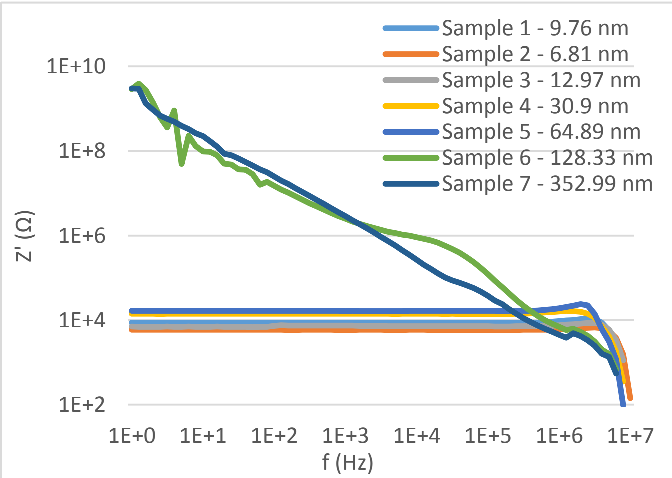

Figure 1. Real impedance response (Z') for SiO_2 samples of varying thicknesses taken in fall 2014.

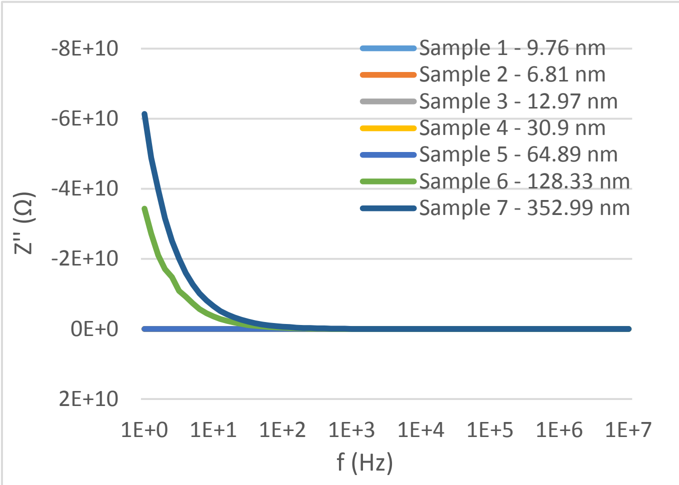

Figure 2. Imaginary impedance response (Z") for SiO_2 samples of varying thicknesses taken in fall 2014.

TechConnect Briefs 2016, TechConnect.org, ISBN 978-0-9975-1170-3

2.3 Edge Effects Analysis

While the results of the experimentation revealed several things, they were not conclusive enough to make an encompassing statement regarding the role of edge effects in electrical characterization of samples with varying thicknesses. The resulting data is shown in Figures 4 and 5.

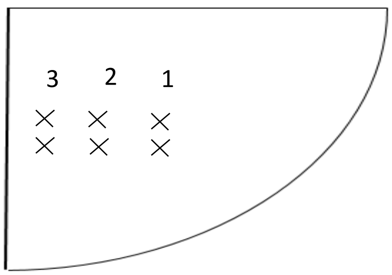

Figure 3. Diagram showing locations of edge effects measurements for SiO_2 samples.

2.4 Environmental Factors

Upon analyzing the results in Figures 4 and 5, it was noted that specifically for sample 6, a large discrepancy was observed that became a topic of interest when examining the data further. The presence of inhomogeneities within the samples still remain a potential reason for the unexpected impedance response, as well as measurement of the film's substrate rather than the actual deposited material, because the measurements were made by manually lowering the probes onto the sample, which could account for some possible sources of error. However, it was a completely contrasting impedance response for one of the thicker samples, which led to consideration of external factors that might alter the composition of the material itself. One of these factors was the humidity levels present in the testing environment, a factor that is not always normally considered when making electrical property measurements and performing characterization of thin film materials.

2.5 Humidity Levels on Impedance Response

The relative humidity levels during the fall of 2014 were in the less than 40% range. In fall 2015, the relative humidity saw an increase and demonstrated a range anywhere from 60-70%. According to the ASTM (American Society for Testing and Materials) Standard D-150, humidity's presence in the air affects an insulating material by increasing the magnitude of its interfacial polarization. This in turn also increases the material's permittivity and loss index, and finally its DC conductance [5]. One would not expect humidity levels to play such a large role in a sample's resulting impedance response, but there is actually data to substantiate this potential variable.

In a published 1996 study on bulk silica

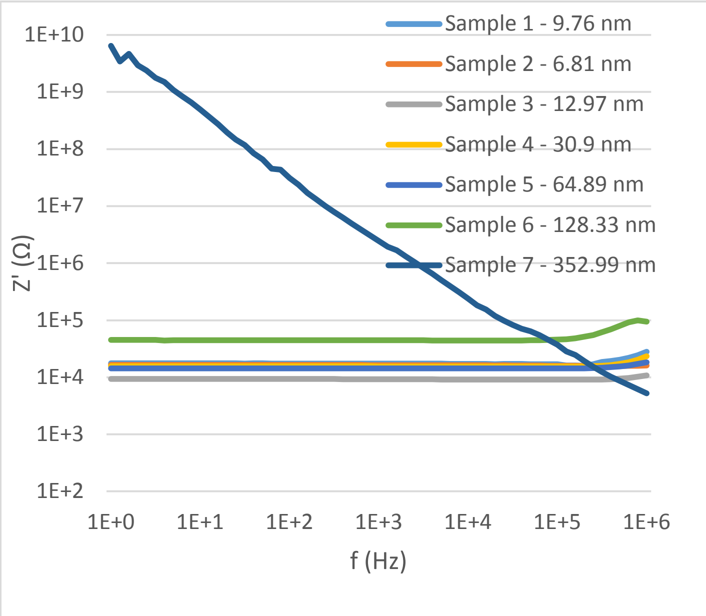

Figure 4. Real impedance response (Z') for SiO_2 samples of varying thicknesses, with measurements taken during fall 2015 at the center location (1) in Figure 3.

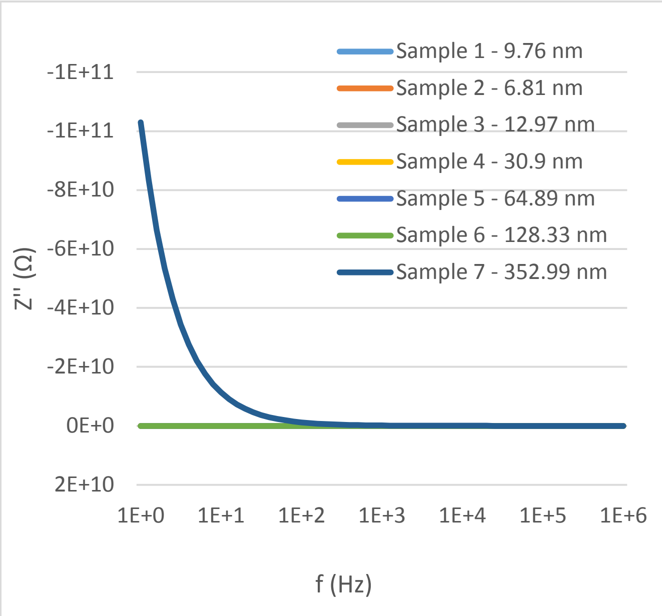

Figure 5. Imaginary impedance response (Z'') for SiO_2 samples of varying thicknesses, with measurements taken during fall 2015 at the center location (1) in Figure 3.

samples[7], relative humidity levels were varied in a range across 25% RH to 86% RH. The data for this study was graphed as imaginary electric modulus vs log frequency as shown in Figure 6 below[7]. One can see the peak of the imaginary electric modulus shifting rightward as the relative humidity increases. There are additional effects observed such as changing the electrical conductivity by several orders of magnitude (not shown).

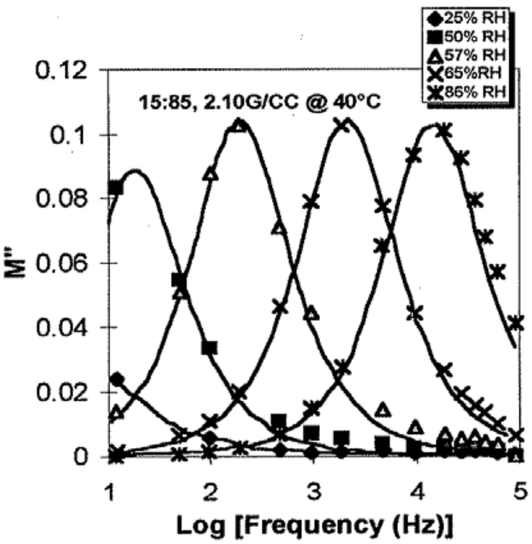

Figure 6. Imaginary electric modulus for a sol-gel silica sample exposed to different ranges of humidity[7].

Electric modulus, *M**, is equal to the inverse of permittivity and thus as the modulus changes, the permittivity will change as well. Electric modulus and permittivity both are electrical responses that can be used to characterize a material. A changing electric modulus or permittivity implies that the impedance response will also be different. It should be added that electric modulus is the dielectric function of choice when characterizing glassy materials such as SiO_2 [8].

3 Conclusions

Based on the results seen through simulation, as well as experimentation, it can be established that a film's thickness does have an impact on its resulting impedance response. Thinner films will generally show a more conductive behavior, especially if deposited on a substrate which is conducting. This is merely because there is less distance between the surface of the insulating deposited material and the substrate.

Several factors can contribute to unexpected impedance responses, but it is important to consider external factors that could potentially contaminate the surface of a thin film. Along with not maintaining standardized humidity levels in the lab, contaminants can reach samples through improper handling (i.e. not wearing gloves) or even exposure to air through which particles like dust can end up on the sample's surface. Other reasons could be the sample's orientation, in which certain parts of the surface could be more exposed to the surrounding air as part of the substrate while making measurements.

3.1 Future Work

In the past few weeks, new samples have been obtained of SiO_2 fabricated via thermal oxidation and PECVD as well. The thermally oxidized samples because of their fabrication process will be more uniform in composition, and are expected to provide more repeatable electrical measurements.

Using these new samples, impedance measurements will be carried out in a similar manner as described in the previous sections. However, this time an automated four-point probe custom-made machine will measure the response of circular wafers at multiple locations, minimizing exposure to air around the sample. Results from these new experiments will be included in the poster presentation for which this report was prepared.

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