Capacitance Based Scanner for Thickness Mapping of Thin Dielectric Films

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Abstract

We have developed a technique capable of mapping variations in the thickness of thin dielectric films, such as organic photoreceptors. This technique is based on accurately recording the capacitance between a spherical probe and the conductive substrate of a dielectric film. Once the capacitance has been recorded, and assuming the dielectric constant is known, the thickness of the film can be readily extracted. In the current experimental configuration, the probe can be raster scanned with respect to the surface of the dielectric film, enabling one to record 3D images and observe any spatial variations in sample thickness. The spatial and thickness resolution of the technique is primarily dictated by the size of the probe. This technique is applicable to any dielectric film on a conductive substrate, assuming the dielectric constant is known.

Introduction

In order to fully characterize and understand the electrical, optical and mechanical properties of thin dielectric films it is crucial to accurately record the film thickness. There are several different methods, including many commercial systems, for measuring thickness, the majority of which are based on either optical technology (interferometry, infrared interference patterns, etc) or capacitance measurements.[1–3] The optical techniques are capable of accurate thickness measurements, but are typically limited to transparent or semi-transparent films. The capacitance methods (also capable of high accuracy) are applicable to any dielectric film, regardless of optical properties. Thus far, the main drawbacks of the capacitance based techniques have originated from the use of a planar probe in an attempt to mimic a parallel plate capacitor. This geometry simplifies the mathematical model, but imposes stringent requirements on the experimental configuration. To record accurate thickness measurements, the planar probe and sample surface must be perfectly parallel, any deviation in alignment will compromise the accuracy of the results. To align the surfaces to the required degree of precision is often very difficult and expensive, particularly if the sample possesses any curvature.

We have previously reported a novel method for recording the thickness of thin dielectric films.[4] This technique is based on accurately recording the capacitance between a *spherical* probe and the conductive substrate of a thin dielectric film. This design complicates the mathematical model, but greatly reduces the requirements for perfect alignment. This spherical capacitive probe technique is readily applicable to any dielectric film with a conductive substrate, regardless of optical properties or sample geometry. The spherical capacitance probe is configured in such a manner that it can be raster scanned with respect to the sample surface. This permits 3D imaging of the sample, with contrast based on variations in local thickness. Therefore, the instrument is not only capable of point thickness measurements, but of high spatial resolution thickness mapping. The spatial or imaging resolution of the technique is primarily dictated by probe size.

Instrumentation and Experimental Details

Probe Design

The primary criteria for the fabrication of a spherical probe are the use of a highly conductive material and a near perfect spherical geometry. The logical choice, considering these criteria, is to use stainless steel ball bearings as they are both inexpensive and readily available in various sizes. We have successfully constructed many probes with ball bearings varying in size from 1-7 mm in diameter, with the smallest diameter balls capable of providing the highest imaging resolution. Figure 1 depicts a typical probe in contact with a thin dielectric film. The electrical contacts for the capacitance measurements, also visible in Figure 1, must be attached to the ball bearing and the conductive substrate of the dielectric film. The electrical leads can be attached several different ways; regardless of which method is implemented, the contact must be stable and possess low impedance in order to ensure a reproducible signal. Another important aspect of the probe, also visible in Figure 1, is the use of grounded shielding. The shield will eliminate any stray capacitance and thus improve the relative magnitude of the useful signal.

Capacitance Detection Scheme

This technique is based on extracting the film thickness from the measured capacitance. Therefore, the accuracy of the thickness measurements will be dictated by the accuracy of the capacitance measurements. We have utilized several

different techniques for measuring the capacitance. The simplest method involves the use of a commercially available capacitance bridge, such as the Andeen-Hagerling 2500A 1 kHz Ultra-Precision capacitance bridge. An alternative method involves the use of a home built charge sensitive amplifier. The charge sensitive amplifier offers the advantages of cost and higher bandwidth.

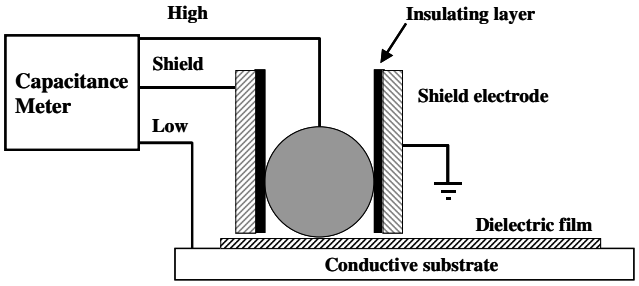

Figure 1. A schematic of the apex of the spherical capacitance probe in contact with a dielectric film. In order to record the capacitance measurements, electrical leads must be attached to the ball bearing and the conductive substrate of the dielectric film. The grounded shielding is needed to eliminate any stray capacitance and improve the reproducibility of the measurements.

Theoretical Model and Calibration

As previously mentioned the mathematical model for the relationship between capacitance and separation for a spherical probe is more complicated than for a planar probe. Since the experimental configuration is highly symmetrical (i.e. a spherical probe), one can utilize the method of images. Basically, the electric field is calculated by substituting the conducting body with equivalent charges, called images. The problem can then be solved as if the conductor were not present, but with a charge distribution composed of the original charges and the corresponding image charges. The capacitance between the a sphere and a plane is given by Eq. (1) and Eq. (2):

$$C = 4\pi\varepsilon_0 R \sum_{n=0}^{\infty} \left\{ \prod_{k=1}^{n} \frac{R}{b - x_{k-1}} \right\}, \qquad (1)$$

where,

$$x_n = \frac{R^2}{b - x_{n-1}} \quad , \quad n = 1,2,..... \quad x_0 = 0 \qquad , \qquad (2)$$

R is the sphere radius, b is the distance between the center of the sphere and the center of its image, and e_o is the vacuum permittivity constant (8.85×10^{-12} F/m)[5]. If the above equations properly model the experiment, one should observe a near exact correlation between the theoretical data and recorded data. Figure 2 is a graph clearly illustrating the excellent agreement between theory and experiment (for a sphere of diameter 6.35 mm). The raw data was recorded by measuring the capacitance of dielectric films of known thickness. The theoretical curve was plotted assuming a dielectric constant of 3.1 (the dielectric film is assumed to be electrically equivalent to an "air film" the same dielectric thickness). It should be noted that for the theoretical data to fit the raw data it must be shifted vertically. The vertical shift accounts for the reduction of the mutual capacitance between the sphere and the conductive substrate due to the presence of the shield. It should be noted that the reduction of the mutual capacitance between the probe and the substrate, due to the shielding, is not affecting the thickness measurements, as the distance dependent component of the capacitance is dominated by the region where the probe and substrate are in the closest proximity and the field lines are approximately normal. The excellent agreement between theory and the experimentally observed data provides a simple means for calibration.

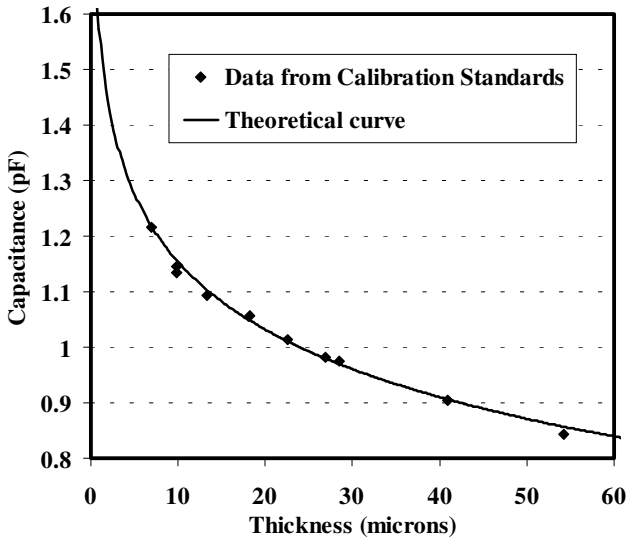

Figure 2. A capacitance vs distance graph containing both the theoretical curve and experimentally observed data from calibration standards. The excellent agreement between theory and experiment is clearly visible. The probe used possessed a diameter of 6.35 mm.

Scanner Assembly

The heart of the technique is the probe and the electronics for detecting capacitance, with the rest of the scanner assembly responsible for supporting the probe and dielectric film, and for the relative motion between them. The dielectric film is mounted on an isolated rotating drum, while the probe is attached to an x-y stage. The rotation of the drum is responsible for motion in the fast scan direction while a stepper motor controls the motion in the slow scan direction. The use of a linear bearing for mounting the probe ensures the force exerted on the sample is limited to the mass of the probe and its holder. The input of the charge

sensitive amplifier is connected to the probe, while the output is fed directly into the data acquisition board (DAQ). The entire experiment is computer controlled, which allows the user to dictate the size and resolution of the thickness image.

Sample Deformation

Since the technique relies on probe-sample contact, sample deformation must be taken into account. A certain amount of elastic (reversible) deformation is inevitable and will undoubtedly influence the data. Fortunately, the magnitude of the deformation is readily calculated using Hertzian contact mechanics.[6] According to Hertzian contact mechanics the elastic deformation is given by Eq. (3):

$$F = \frac{4}{3} E^* R_r^{1/2} D^{3/2} \quad , \qquad (3)$$

where $E^*=((1-\nu_s^2)/ E_s +(1- \nu_p^2)/E_p)^{-1}$ and $R_r=(1/R_s + 1/R_p)^{-1}$, E^* is the reduced elastic modulus, E is elastic modulus, ν is the Poisson's ratio, R_r is the reduced radius, R is the radius and D is the depth of penetration, with the subscripts s and p denoting sample and probe respectively.

A typical probe/holder assembly weighs 10g and therefore exerts a force of 98 mN. Assuming a sample elastic modulus between ~3 GPa and a probe diameter of 6.35 mm, the depth of penetration is estimated to be ~600 nm. In other words, the true thickness is ~600 nm larger than the measured thickness. It would be possible to significantly reduce the amount of deformation by simply using a lighter probe/holder assembly.

Examples of Thickness Images

The advantage of this thickness scanner over most other techniques is the ability to image. Imaging not only allows one to record and average substantial amounts of thickness data, but it aids in identifying any spatial variations in thickness across a given sample. The device most frequently used for testing and optimizing the imaging capabilities of the thickness scanner was a polycarbonate film. Figure 3 shows two thickness images recorded with a 3.175 mm diameter probe. The images were generated by raster scanning the probe in a rectangular geometry, while recording the individual data points (or pixels). The contrast in the images corresponds to variations in the film thickness. Both images were recorded from the same area, with Figure 3b being recorded immediately after Figure 3a. The average thickness of the sampled area (20 mm x 20 mm) was 25.4 ± 0.5 μm for Figure 3a and 25.3 ± 0.4 μm for Figure 3b, assuming a dielectric constant of 3. It should be noted that the stated error does not necessarily represent the inherent error in the technique, but is more of a reflection of the variation in film thickness. The images are nearly identical in appearance and average thickness, thereby confirming the reproducibility of the technique. Another test of the reproducibility of the technique is shown in Figure 4. Figure 4 represents line cuts taken from the same location in Figures 3a and 3b. As expected the two line cuts, from successive scans, are nearly identical, once again confirming the reproducibility of the technique. If the images were nothing but random noise, the two images would bear no resemblance and the line cuts would therefore be arbitrary profiles. The profiles of the two line cuts overlap nearly perfectly, with a small amount of noise, corresponding to less than 0.2 μm, superimposed on both profiles.

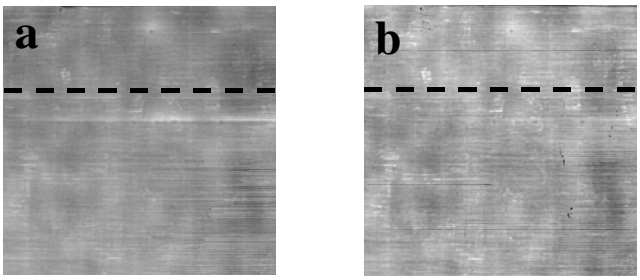

Figure 3. Thickness images, 20 mm x 20 mm, of a polycarbonate film that possesses a conductive substrate. Image b) was recorded immediately after image a). The two images are nearly identical illustrating the reproducibility of the technique. The dashed white lines visible across both images represent the position of the line cuts, which are shown in Figure 4. The line cuts were taken at the same location in each image.

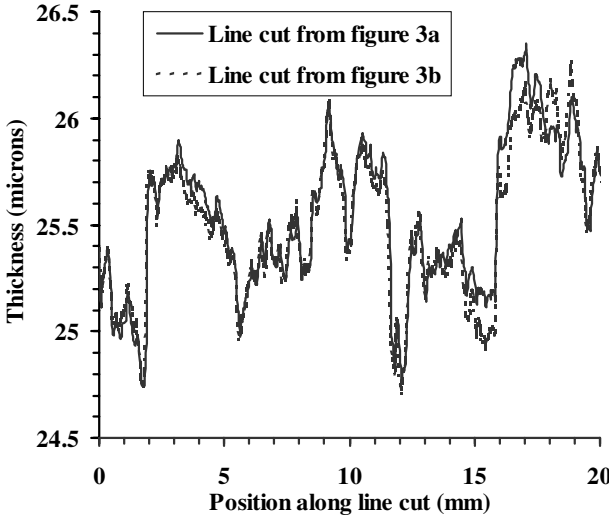

Figure 4. A graph of thickness vs position for the line cuts taken from images 3a) and 3b). The line cuts were taken from the same location in each image. It is evident from the graph that the profile of the two line cuts is nearly identical, once again confirming the reproducibility of the technique.

Conclusions

We have constructed a thickness scanner based on a spherical capacitance probe, which is capable of recording both point measurements and thickness images of thin dielectric films. The spatial and thickness resolution of the

probe is primarily dictated by probe size. The applicability of this technique extends beyond polymer films, since it is capable of accurately recording the thickness of any thin dielectric film on a conductive substrate.

Acknowledgements

The authors gratefully acknowledge Geoff Allen for the preparation of the thin film samples. The technical assistance of Samy Mesbah is also gratefully acknowledged.

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Biography

John Graham received his B.Sc. degree in Chemistry from McMaster University in 1994 and Ph.D. in Physical Chemistry from the University of Western Ontario in 1999. In the same year he joined the Xerox Research Centre of Canada (XRCC) and is involved in the characterization of new photoreceptor materials. Dr. Graham's main research interests are in xerographic physics, surface chemistry and the development of novel characterization tools.