Non-Contact Imaging of Dielectric Constant with a Near-Field Scanning Microwave Microscope

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SUMMARY
We describe a non-contact technique for imaging dielectric constant using a resonant near-field scanning microwave microscope. By measuring the shift in the system's resonant frequency as we scan over an insulating sample, we obtain quantitative images of dielectric variations. We scanned seven samples with dielectric constants ranging from 1 to 230, using a 480 μm diameter probe at a height of 100 μm and a frequency of 9.08 GHz. The technique achieves an accuracy of about 25% for ε = 230 and less than 2% for ε = 2.1, limited mainly by variations in the probe-sample separation.

INTRODUCTION
The ability to image variations in relative permittivity or dielectric constant ε is useful for a variety of applications. For example, in thin-film microelectronics, testing for variations in dielectric constant can be useful for quality control or to develop better growth techniques. As another example, knowledge of the dielectric constant at microwave frequencies is of great importance for the design of broadband circuits. Nowadays numerous techniques exist for measuring the dielectric constant and loss tangent of insulating materials at microwave frequencies [1-6]. However, most of these techniques involve working in contact and require thick homogeneous samples [1,2,4]. In this article, we report on the use of a resonant near-field scanning microwave microscope for the non-contact imaging of dielectric samples. Our approach offers a fast, simple, broadband method to image dielectrics using readily available microwave components.

Our resonant near-field scanning microwave microscope consists of a 1 m long coaxial transmission line which is capacitively coupled to a microwave source at one end and terminated by an open-ended coaxial probe at the other end. This arrangement creates a resonant circuit in which the resonant frequency f₀ and quality factor Q are modified when a sample approaches the open end of the probe (see inset in Fig. 1). By using a frequency-following feedback circuit we keep the microwave source locked on resonance [7]. We measure the shift of the system’s resonant frequency Δf as we scan the sample under the probe. The variations in Δf are directly related to spatial variations in dielectric constant in the sample. In addition, however, topographic changes will also give rise to changes in Δf [8].

CALIBRATION
To calibrate the system, we constructed a test sample by placing six pieces of different dielectric material into the bottom of a square plastic mould and pouring epoxy into the mould. In addition, silicone adhesive was used to hold each piece down. After the epoxy cured, the test sample was removed from the mould, polished, and positioned on the XY table. The materials embedded in the epoxy were silicon, glass microscope slide, SrTiO₃, Teflon, sapphire, and LaAlO₃. All six pieces were approximately 500 μm thick and about 6 mm x 8 mm in size. The overall thickness of the test sample was 6 mm.

We measured the frequency shift Δf versus height h above the six pieces, which have dielectric constants ranging from 2.1 to about...
We also tested the epoxy which has an unknown dielectric constant. Each piece, as well as the probe, was flat and smooth on the scale of 5 μm as judged by an optical microscope. For these measurements, we used a probe with a 480 μm center conductor diameter and a source frequency of 9.08 GHz. For each scan, the probe was first brought in contact with a dielectric and the frequency shift measured was recorded as the height was systematically increased. The results are plotted in Fig. 1. Samples with the largest dielectric constant produced the largest frequency shift as expected. The largest shift we observed was -26.2 MHz, when the probe was in contact with a SrTiO3 sample with εr = 230 [9]. The smallest shift we found was -1.2 MHz when the probe was in contact with a Teflon sample with εr = 2.1 [9]. As can be seen from Fig. 1, the frequency shift is essentially zero above 1 mm and saturates when the probe-sample distance is smaller than a few microns.

We used the above information to construct an empirical calibration curve that directly relates frequency shift to the dielectric constant. In order to construct the calibration curve we took the difference between the measured frequency shift at two separate heights h1 and h2, i.e. f = (f2 - f1)/h, where h2 is far away (h2 > 1000 μm), by taking the difference, we eliminated the effect of drift in the microwave source frequency. Proceeding this way for the test samples, we constructed two calibration curves of f versus εr (see Fig. 2), one curve for h2 = 100 μm and h1 = 1.1 mm and the other for h2 = 100 μm and h1 = 1.1 μm. We then set the parameters for each calibration curve with an empirical function (solid lines in Fig. 2), allowing us to easily transform any measured frequency shift to a dielectric constant. From these curves we can see that we can enhance the sensitivity to the dielectric constant considerably by using a small probe height. On the other hand, at closer probe-sample separations the influence of topographic features will be enhanced.

**IMAGING RESULTS**

To test the dielectric imaging capabilities of our system, we next scanned a single sample of LaAlO3, which had an 8 x 5 mm triangular shape and a thickness of 510 μm. We placed the sample directly on the metal scanning table and recorded the frequency shift as a function of position. The data was taken at 9.08 GHz using the 480 μm probe at heights of 100 μm and 1.1 mm. We subtracted the two data sets and used our 100 μm calibration curve to transform the resulting frequency shift image into a dielectric constant image. Figure 3 shows the resulting contour image of dielectric constant versus position. The dielectric constant varies from about 20 to 25 over the sample and equals 1 when the probe is away from the sample. For comparison, the reported values of relative permittivity are 22.3 [10]. In this image, the main variation in εr over the sample is due to a slight tilt in the sample surface of about 20 μm. The edges of the sample show a smaller value of εr due to averaging over the inner conductor of the probe. The width of the affected region is in good agreement with the expected spatial resolution of about 500 μm.

We next recorded a frequency shift image of a piece of test sample using a probe-sample separation of 100 μm and the 480 μm diameter probe at 9.08 GHz. As before, using the f(εr) calibration, we then transformed the frequency shift image into a dielectric constant image (see Fig. 4a). The darker regions in Fig. 4a indicate a higher dielectric constant (larger frequency shift) and the lighter regions indicate a smaller dielectric constant (smaller frequency shift). Figure 4b shows the corresponding surface plot representation. Note that the z-axis in Fig. 4b uses a logarithmic scale to allow us to show the large range of dielectric constants present in the sample. As expected, the largest dielectric constant materials (SrTiO3 and LaAlO3) are the highest surfaces and the smallest dielectric constant materials (Teflon and vacuum) are the lowest. Further, notice that the Teflon sample forms a depression in Fig. 4b, indicating that the dielectric constant of Teflon is lower than the surrounding epoxy. We also note that voids in the epoxy can easily be seen as irregularly shaped low-dielectric regions (white regions.
in Fig. 4a) in the epoxy. Table 1 summarizes the dielectric constants found from Fig. 4 for the six test materials.

From Fig. 4b, it is apparent that there is some noise in our images of dielectric constant. In our system, the predominant sources of random error are noise in our recording electronics and fluctuations in the source frequency. To establish the precision to which \( \varepsilon_r \) can be determined, we determined the standard deviation in \( \varepsilon_r \) over a small region near the center of the \( \text{LaAlO}_3 \) sample in Fig. 3; we found \( \sigma_{\varepsilon_r} = 0.06 \) for a sampling time of 30 ms. Similarly, over the \( \text{Teflon} \) in Fig. 4a, the standard deviation in \( \varepsilon_r \) was 7\( \times \)10\(^{-4} \) for a sampling time of 30 ms. From Fig. 4 we can also estimate the absolute accuracy of our technique. For \( \varepsilon_r = 230 \) \( \text{SrTiO}_3 \), the accuracy is about 25% while for \( \varepsilon_r = 2.1 \) \( \text{Teflon} \) the accuracy is better than 2%. The main source of these errors is topographic variations; in our test sample, even after polishing, there are small height variations of about 30 \( \mu \)m (e.g. between the \( \text{sapphire} \) and \( \text{SrTiO}_3 \) in Fig. 4) between the different dielectrics. Such height variations cause an additional frequency shift \( [8] \), resulting in an error in the measured dielectric constant. In this regard, an accurate measurement of the dielectric constant of a single flat dielectric sample is considerably easier. However, the image of the composite sample clearly demonstrates the strength and sensitivity of this noncontact technique to measure variations in \( \varepsilon_r \).

CONCLUSIONS
In summary, we have used an open-ended, resonant, near-field scanning microwave microscope to obtain quantitative images of the dielectric constant of bulk materials. Our system allows for fast, reliable, non-contact imaging of variations in the dielectric constant of flat samples, provided that the height of the probe above the sample is accurately controlled.

ACKNOWLEDGEMENTS
We acknowledge support from the National Science Foundation NSF-MRSEC grant No. DMR-9632521, NSF grant No. ECS-930243, and from the Maryland Center for Superconductivity Research.

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