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Imaging the microscopic properties of dielectrics via potential and charge

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Abstract—**In this paper we discuss an application of a high spatial resolution raster scanning microscope (step size 6 microns) capable of measuring static charge or a.c. potentials via weak capacitive coupling. It is based on an ultra high impedance electric field sensor, developed and patented at the University of Sussex. Results are reported for low frequency (350 Hz) measurements of a composite dielectric (FR4 circuit board) which reveal both surface and buried defects, in addition to differentiating the material structure. The results have sufficient contrast to allow both the epoxy resin and glass mat to be seen. This method could find application in the characterization of insulators or dielectrics or in the testing for defects such as inclusions or water ingress, or the uniformity of materials properties. A second mode of operation of the sensor will also be described which allows surface charge density imaging to be performed and unambiguously distinguished from the measurement of AC surface potential described above.**

I. INTRODUCTION

Scanning probe microscopy is a powerful tool for the measurement of various surface properties. However, Scanning Tunneling Microscopy [1] and the various modes of Atomic Force Microscopy [2] rely on the forces that exist between a probe and sample when separated on an atomic length scale. This results in excellent atomic resolution but enforces careful control of the probe position. Here we discuss a new method, which uses a scanning Electric Potential Sensor (EPS), which can operate at a flexible resolution scale, allowing a trade-off between scanning speed and spatial resolution. This technique fulfils the need for microscopic surface measurement at coarser length scales where atomic resolution scanning probe microscopy becomes cumbersome and slow. The probe consists of an ultra-high impedance Electric Potential Sensor [3] developed and patented at the University of Sussex, along with a carefully defined electrode structure. The sensor measures surface electric potential via non-contact, weak capacitive coupling. Since no real charge current is drawn by the sensor, a true non-invasive measure of electric potential is possible with no risk of sample damage by high current densities at the electrode-sample interface.

The EPS sensor provides a direct measure of electric potential, enabling several unique measurement modes. The EPS as a scanning microscope has been previously introduced as a tool for imaging VLSI circuits non-destructively [4]. Here we present results from two new measurement modes for AC and DC potentials respectively, which have been performed with a scanning system that represents a significant improvement over previous efforts. With the AC mode we show that surface topography can be determined for conducting and dielectric samples, and buried defects can be revealed and differentiated from surface topography in dielectric samples. With the DC measurement mode we demonstrate the measurement of static surface charge density on thin insulating materials. Two major advances have been made over the previous system, namely, significant improvements to the generic EPS sensor have negated the need to 'tune' the sensor for a narrow frequency band [4], enabling broadband AC measurements with lower noise and higher sensitivity than before, with previously unobtainable electrical stability. Secondly, the sensor is paired with a more robust electrode structure that can withstand significant mechanical and environmental stress.

II. METHOD

This discussion shall be initially limited to the AC measurement mode, and we shall only consider DC measurement afterwards, since it is in fact only a special case of the AC measurement. An image is constructed by scanning an electric potential sensor, usually at constant height, above a sample and making many point measurements. An electric potential sensor consists of a high impedance electrometer amplifier along with circuitry to provide a stable DC bias current and minimize input capacitance through several guarding and feedback techniques. The EPS has no long term DC drift and is inherently stable. The EPS is able to non-invasively measure spatial electric potential in a broad bandwidth from a few mHz to tens of MHz [5] with high sensitivity and low noise due to its high input impedance of 10^{13} Ω with a corresponding input capacitance of 10^{-16} F.

The scanned EPS probe is used to make many point measurements in order to construct an image. We therefore refer to each measurement as a pixel. The probe's response to the pixel beneath it and the additional contribution to the measured potential due to those pixels adjacent to it can be described by a spatial sensitivity function. For our imaging purposes we assume a step sensitivity function and therefore neglect contributions from adjacent pixels, though it is possible to account for this inaccuracy by using a measured or calculated spatial sensitivity function and inversion methods [6]. We have found by finite-element modeling (FEM) of the probe response and through measurement that this approximation is quite satisfactory. We use a co-axial electrode structure that is designed to minimize adjacent pixel's influence on the probe. The electrode consists of a 5 μm diameter insulated micro-wire coated in silver paint and set in epoxy resin. The electrode is terminated by an SMA connector in order to exchange electrodes on the EPS. The silver paint forms a coaxial guard around the sense electrode, spaced by no more than 1 μm, in order to confine the electrodes spatial sensitivity. We have found by FEM that the diameter of the guard electrode is of supreme importance in defining the spatial sensitivity of the probe. When this 5 μm probe is spaced from a sample by 5 μm, we find that the resolution of the imaging system is also 5 μm. When the sample-probe spacing is increased resolution drops off approximately linearly with spacing. As such the system allows flexibility in spatial resolution, allowing scanning to be performed at higher speed over larger areas with reduced resolution.

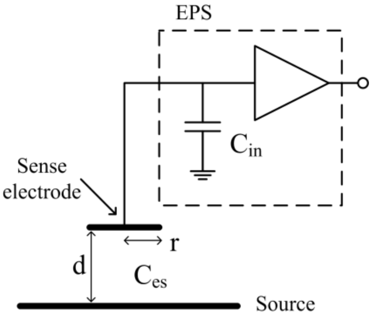


Fig. 1. Sensor and electrode geometry. C_{es} is the capacitance formed between the sense electrode and the source, C_{in} is the total input capacitance of the EPS sensor and electrode structure.

The EPS couples capacitively to the source of electric potential. A capacitive divider is therefore formed between the electrode-source capacitance, C_{es}, and the input capacitance (capacitance to ground) of the EPS, C_{in}, as shown in figure 1. This divider ratio sets the sensitivity of the microscope. Since the guarding of the input electrode confines the effective area to the diameter of the centre sense electrode, we can use this diameter to approximate C_{es} as a parallel plate capacitor. This approximation has been found to provide the most accurate agreement with experiment, versus more complicated geometries such as the sphere-plane model [7]. This capacitance is then given by Equation 1

$$C_{es} = \frac{\varepsilon_0 \varepsilon_r \pi r^2}{d} \tag{1}$$

Where r is the effective electrode radius and d is the electrode-source separation. The ratio of source potential to EPS output potential is given by

$$\frac{V_{out}}{V_{in}} = \frac{C_{es}}{C_{es} + C_{in}}$$

$$\frac{V_{out}}{V_{in}} = \frac{\alpha}{\alpha + d} \quad where\ \alpha = \frac{\varepsilon_0 \varepsilon_r \pi r^2}{C_{in}} \tag{2}$$

Using the 5 μm diameter electrode and an electrode-source separation of 5 μm, where resolution is maximized, this ratio is found to be 0.7 for an EPS input capacitance of 0.1 fF, assuming ε_r=1 in air. The EPS input capacitance is found by measuring the EPS response through a calibrated test capacitor. With the EPS' input referred noise voltage of 10 μV/$\sqrt{Hz}$, surface potentials of a few tens of millivolts may be detected in a broadband measurement, with scope to significantly improve this sensitivity using narrow band or lock-in measurements. Performing this calculation illustrates the importance of extremely low input capacitance when performing high spatial resolution measurements. Since it is clear that a larger sense electrode increases sensitivity, we have produced a larger 100 μm diameter electrode for performing high speed, low resolution measurements.

The scanning hardware consists of a two-axis gantry table with linear slide bearings and stepper motor driven ball screws allowing 6 μm positional resolution over a large 300 mm x 300 mm scan area. The EPS probe is mounted on the gantry via another stepper motor and screw to provide linear z-axis control to set the sample-probe separation. This hardware is controlled by a custom built stepper driver and data acquisition system which interfaces to a PC running LabView software [8]. This hardware/software system allows automated scanning and image generation.

From Equation 2 it is clear that the sensor output voltage is proportional to electrode-source separation, *d*. This then forms the basis of a surface topography measurement. For small deviations about the nominal working distance, the AC output voltage of the sensor can be translated to a measure of electrode-source separation, and therefore the surface topography of the source electrode. The ratio of output to source amplitude is plotted in Figure 2 for the 5 μm diameter electrode, calculated using Equation 2. For conducting samples this measurement is performed by applying an AC potential to the sample and measuring the sensor output amplitude using a lock-in amplifier. Our scanning hardware/software system is able to supply the necessary AC signal and perform a lock-in measurement in software.

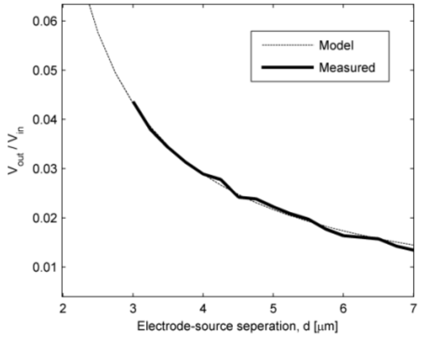


Fig. 2. Vout/Vin (from Equation 2) for a sense electrode with r = 2.5 μm and a probe input capacitance of 1 fF, as a function of source-electrode separation, *d*. The Model matches measurements well when *d* is approximately equal to *r*.

Thin dielectric samples may also be measured using an identical technique by applying the source AC potential to a conducting plane beneath the sample. For a material of uniform dielectric constant the image produced from amplitude information is purely topographical. Where variations in dielectric constant exist, the according variation in electrode-source capacitance produces amplitude variations apparent in the final image. In this manner buried defects and discontinuities may be revealed, which is of particular use for checking consistency in composite materials. The present system operates at frequencies in the range 10 Hz to 100 kHz, although it is possible to extend this range through the use of specialized high-frequency EPS sensors.

A second distinct measurement mode allows the imaging of DC potentials on surfaces. This method is completely passive and requires no active signal source. This method has previously been applied using arrays of EPS sensors for imaging charge at a macroscopic scale [9] and has a noise floor in units of surface charge density of 5 pC cm^{-2}. Due to the high impedance of the EPS sensor, no charge is removed during the measurement allowing charge decay processes to be observed [10]. By applying this technique with the microscopic probe we can now image DC potentials at high spatial resolution and with increased sensitivity.

This DC measurement technique differs from traditional electrostatic probes [11] in two significant ways. First, it measures spatial potential gradient from one pixel measurement to the next, negating errors caused by DC drift in the sensor. This is achieved by allowing the voltage induced on the probe during a point measurement to decay over the short input time constant of the sensor formed between the very low input capacitance and a well defined input resistance of 10^{11} Ω or less. Upon moving the sensor to the next measurement pixel, any change in spatial potential between the two points results in an impulse on the sensor proportional to the potential gradient between the two measurement points. The second benefit over conventional methods is the vast range of potentials which can be measured. Straightforward adjustment of the sensitivity of the probe allows electrostatic potentials from several kilo-volts down to source potentials of a few volts to be measured. This is achieved by adjusting the input capacitance of the probe in order to utilize the capacitive divider inherent in the measurement to reduce higher voltages to a safe level. The maximum measurable potential is limited only by electrical breakdown over the source-electrode capacitance, which is expected to occur at levels greater than 10 kV when operating at maximum spatial resolution. When breakdown does occur, ESD protection on the EPS input will protect the sensor from damage.

III. RESULTS

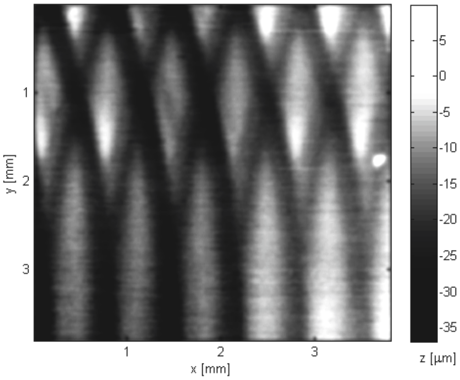


Fig. 3. Topographical image of a conducting sample. The sample is a machined surface roughness reference; in this case the roughness is 30 µm peak to peak.

An example of the first mode of measurement is the surface topography of conducting samples and provides the most straightforward measurement situation. The image created by the amplitude of the sensor output, as a function of position, can be translated directly to a surface topography map (Figure 3). Electrode-sample separation may be found by solving Equation 2 for *d*. This gives;

$$d = \alpha\left(\frac{1}{V} - 1\right) \tag{3}$$

This separation value is then subtracted from the nominal working distance (defined at pixel 0, bottom right of image) to give *z,* the height at each pixel, where positive values indicate a high area on the sample. Figure 3 is formed from 90 k-pixels on a 300 by 300 grid. Each pixel is spaced by 12.6 µm, producing a 3.8mm x 3.8mm image. The time required to produce an image is limited by the positioning system velocity and the probe output amplitude measurement time. The maximum speed with our current system is 50 ms per pixel, so that a large image as shown in figure 3 takes 75 minutes to produce.

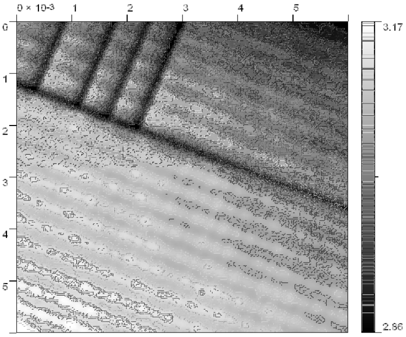
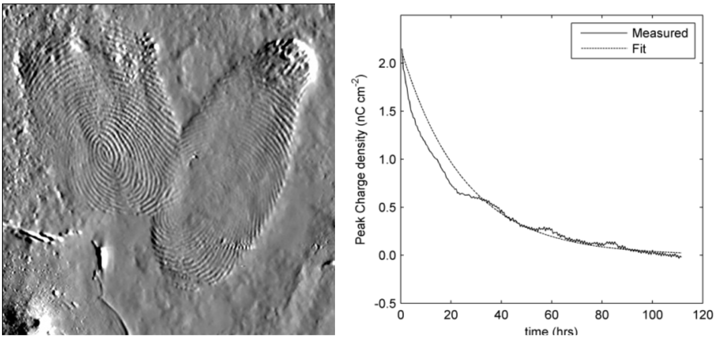


Fig. 4. Composite fiberglass FR-4 PCB material imaged using a 350 Hz AC signal applied to a source electrode underneath the sample. The Z axis scale is output voltage in units of V rms, for a source voltage of 7 V rms. Lines machined into the surface are clearly discernible, as is the underlying fiberglass mat. The image consists of 400 x 400 pixels at 15 µm pitch.

In figure 4 we see another example of the first measurement mode where an image is produced by plotting the sensor output amplitude when scanned over a dielectric sample. This sample has had lines machined (approximate depth 100 µm) into the otherwise flat surface to demonstrate the visibility of surface topography variations in a dielectric sample. Furthermore, the parallel lines across the entire image are due to the underlying glass fiber mat structure, which produces a variation in output amplitude as a result of the slightly different dielectric constants of the glass mat and resin. This dielectric contrast makes it possible to detect buried defects in dielectric materials such as voids or water ingress.



(a) (b)

Fig. 5. Surface charge density for an 80 µm thick PTFE sheet: (a) charge image, 300 x 300 pixels, 120 µm pitch. This charge distribution reveals two latent fingerprints, created by triboelectric charging during momentary contact of a finger with the surface. The scale, from black to white, runs from -1 to +1 nC cm^{-2}. (b) Charge decay versus time for a single pixel measurement. An exponential curve is fitted to the data, with a time constant of 25 hours.

In figure 5 we show an example of the second measurement mode where the charge distribution left by the contact of a finger on a PTFE sheet is revealed. There is sufficient spatial resolution in this image to clearly resolve the fingerprint ridge pattern. Due to the time dependence of the magnitude of the charge in such a latent fingerprint, it may be possible to date or sequence fingerprints for evidential purposes using this technique.

IV. CONCLUSIONS

A novel electric potential sensor has been used to generate images of the microscopic electrical properties of samples. Two modes of operation are demonstrated which allow either the AC or DC surface potential to be measured. Both techniques use the same apparatus and may be performed simultaneously during the same scan. The AC mode is illustrated by imaging the surface topography of a metal sample and by revealing distinct surface and sub-surface features for a dielectric sample. The ability of the DC mode to image static charge distributions is demonstrated by monitoring the decay of a latent fingerprint on a thin insulating sheet. Applications for this instrument include materials testing and forensic science.

V. REFERENCES

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