



Charge Detection Methods for Dielectrics – Overview

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Abstract This paper is intended to provide a brief overview of charge detection methods used in research and in many industrial applications. Attention was brought especially to "macroscopic" methods that are suitable for large quantity and volume investigations of various materials and structures.

1 Introduction

The importance of charge phenomena occurring in dielectrics has been recognized for a long time by many scientists and engineers. Over the years, as electrical and electronic equipment have become smaller and more compact, the insulating materials used are experiencing increasingly higher electrical stresses. It has been found that under such enhanced electric field conditions the charging and charge trapping phenomena are very important factors to be considered when designing insulation systems. A great number of methods and techniques has been developed to investigate space and surface charge distributions in various materials. Trek, Inc. has been recognized for its expertise in non-contact and non-invasive probe methods of surface charge measurements. A broad line of electrostatic voltmeters (ESVM) had been developed in order to accommodate various needs and requirements of scientific and industrial applications. However, it is important to realize that there are also other techniques for measurements of surface and volume charges in various materials. The intention of this overview is to briefly describe the most popular charge measurement technologies available, and, in this way, provide a base for informed choice of the most appropriate technique. All microscopic methods were omitted as they are considered not suitable for high volume tests.

2 Thermal Methods

Thermal techniques are most easily applied to thin films. If used for relatively thick samples, the electric field intensity is allowed to vary only in

the direction normal to the plane of the sample, otherwise the measurement becomes inaccurate. Usually samples tested with thermal methods require poling under DC high voltage with electric field intensities ranging up to 50 [kV/mm] [1]. Either corona or contact poling with high voltages up to 30 [kV] can be conducted with Trek's 30/20 or 20/20C High Voltage Power Amplifiers. For lower voltage requirements other Trek amplifiers can be used.

2.1 Thermal Pulse Methods (TPM).

The idea of this measurement is application of the thermal pulse to one of the surfaces of the investigated dielectric material (Figure 1). The electrical response generated in the sample carries the information about the charge or polarization distribution. Unfortunately, it is a convoluted function of space and time and requires use of appropriate mathematical methods to correctly interpret the results. Also, the time of measurement is relatively long. As a source of thermal pulse, the light flash is frequently used [1–5]. For the purpose of charge or current measurement, Trek's Model 217 Coulombmeter/Ammeter can be employed. Advantages of the method are:

- good resolution (2 [μm]),
- applies to relatively thick samples,
- possible non-contact measurements.

Disadvantages of the TPM technique:

- resulting electrical signal is a convoluted function of space and time and requires advanced mathematical solution methods.



Charge Detection Methods for Dielectrics – Overview

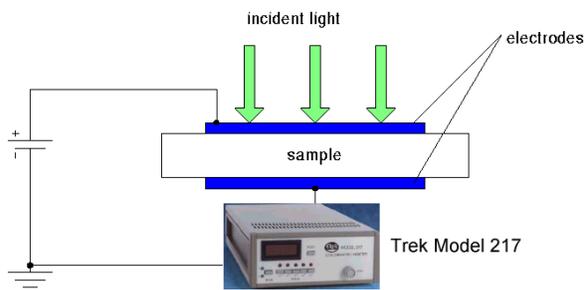


Figure 1: Thermal pulse method measurement setup

2.2 Laser Intensity Modulation Method (LIMM).

This method uses modulated surface heating of the dielectric samples. It produces spatially nonuniform temperature distribution through the thickness of the specimen. The sine-modulated laser beam is often used as a source of the heat wave. Such heat signal causes a sinusoidal fluctuation in temperature of the front electrode and thermal wave penetration into the sample (Figure 2). The waves are attenuated as they progress through the material. An interaction of aforementioned thermal field with space charges present in the sample produces a sinusoidal pyroelectric current [6]. With the thermal wave method it is possible to create a strong temperature oscillation near the surface, but no localized strong oscillation at an arbitrary depth in the sample (this follows from the heat conduction equation). In mathematical terms, the measured current is a convolution of the pyroelectric coefficient $p(x)$ with the temperature distribution:

$$I_{\sim}(\omega) \propto k \int_0^d p(x) \frac{\cosh[k(d-x)]}{\sinh(kd)} dx \quad (1)$$

where

$$k(\omega) = \left(\frac{\omega}{2D} \right)^{1/2} \quad (2)$$

I_{\sim} is a pyroelectric current, D is a thermal diffusivity and d is a thickness of the sample. Unfortunately, solving for $p(x)$ is an ill-conditioned problem and appropriate numerical methods have to be used.

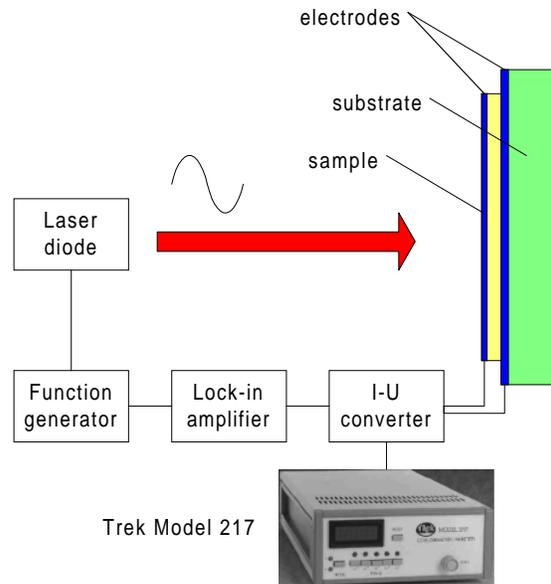


Figure 2: Laser Intensity Modulation Method setup

3 Pressure Pulse Methods (PPM)

There exists quite a number of techniques that can be classified as pressure pulse methods [7–9]. They depend on phenomena occurring when an ultrasonic pulse propagates through the sample (Figure 3). Assuming that the considered material is homogeneous and non-conducting, the current $I(t)$ flowing due to the material's reaction to the external pressure pulse can be described as:

$$I(t) = X \cdot C_0 G(\epsilon_r) \int_0^{z_f} E(z, 0) \frac{\partial}{\partial t} p(z, t) dz \quad (3)$$

Charge Detection Methods for Dielectrics – Overview

where X is the compressibility of the material, $G(\epsilon_r)$ is a function of the relative permittivity (dielectric constant) ϵ_r , which in turn depends on the pressure distribution in the sample. $E(z,0)$ is the electric field distribution at the time $t=0$, $p(z,t)$ is the pressure distribution and C_0 is the capacitance of the non-compressed sample:

$$C_0 = \epsilon_0 \epsilon_r \cdot S/d \tag{4}$$

Where d is the thickness of the sample, S is the sample area.

At the same time, the voltage difference $V(t)$ across the sample is described by:

$$V(t) = X \cdot G(\epsilon_r) \int_0^{z_f} E(z,0)p(z,t) dz \tag{5}$$

The information about charge distribution can be extracted using Poisson's equation:

$$\nabla^2 V = \frac{\rho}{\epsilon_0 \epsilon_r} \tag{6}$$

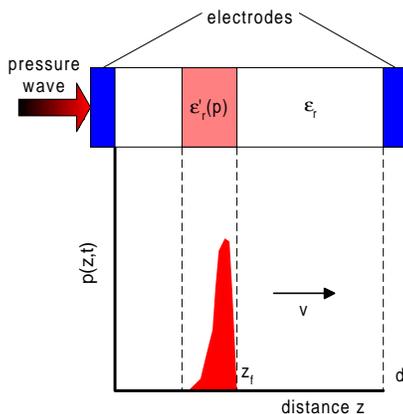


Figure 3: Principle of the Pressure Pulse Methods

Techniques that belong to this family share the same measurement principle, the difference is in the method of initiating the pressure pulse that travels through the measured sample.

3.1 Laser Induced Pressure Pulse Method (LIPP).

The resolution of this method and of all pressure pulse methods depends strictly on the width of the pressure disturbance wave. The pressure wave is generated by absorbing a laser light pulse in a metal target bonded to the dielectric sample. For a very short pulse (around 1 [ns]), the electrical response gives the spatial distribution of the electric field and charge density. This method is used also for surface charge distribution measurements [7, 8, 10, 11].

3.2 Thermoelastically Generated LIPP.

The pressure wave excitation comes from a laser light pulse striking an optically absorbing layer located on one of electrodes. Resolution of this technique is around 1[μ m] [12].

3.3 Piezoelectrically Induced Pressure Pulse (PIPP).

This method is very similar to LIPP method. The pressure wave is generated by a piezoelectric transducer [9, 13].

3.4 Non-Structured Acoustic Pulse Method (NSAPM).

A typical measurement system consists of an acoustic pulse generator, receiver, and a data acquisition system. As a generator of the acoustic signal a high voltage spark is frequently used. For simple dielectric materials a resolution of 1 [mm] has been achieved [14].

Charge Detection Methods for Dielectrics – Overview

3.5 Laser-Generated Acoustic Pulse Method.

In order to improve repeatability and bandwidth of the NSAPM technique, the laser, as a power source, was introduced. This led to the construction of the system shown in Figure 4. The acoustic pulses are created by the laser beam fired on a thin paper target. A 50 [μm] resolution in 3 [mm] thick sample was recorded by using this method [15].

3.6 Acoustic Probe Method.

This method is based on the effect of generation of an electric signal by mechanical excitation of the charged sample. Resolutions of 0.2 [mm] can be achieved using this technique [16].

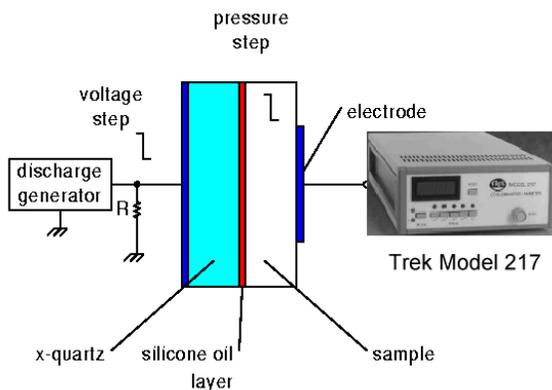


Figure 4: Laser-Generated Acoustic Pulse Method [15]

The major disadvantage of the pressure wave methods is poor reproducibility due to insufficient information about the pressure wave propagation.

4 Electro-Acoustic Stress Pulse Method

The principle of this technique is based upon the Coulomb force law. Externally applied pulsed electric field induces a force perturbation in the presence of resident charges. This creates an acoustic (or pressure) wave in the sample. The acoustic signal can be detected using a piezoelectric transducer. The resolution of this method depends on the duration of the electric pulse and on the thickness of the sample. The density and polarity of the space charge is obtained from the physical characteristics of the acoustic signal. The difficulty lies in the ability to apply the electric stress uniformly. Problems also arise when the charge distribution and polarization profiles are complex. This method is also known as a pulsed electro-acoustic (PEA) technique [17–19].

5 Thermal Step Method

By creating a temperature gradient across the sample the electric current is induced due to thermal expansion of the material. This method is time consuming, although it is non-destructive [20–23].

6 Photoconductivity Method

This technique uses the light absorption phenomena in a thin photoconductive layer [24, 25]. By the detection of the photocurrent produced, the information about the charge distribution can be obtained. This method is relatively accurate and it is nondestructive providing a short illumination time with low light intensity.

Charge Detection Methods for Dielectrics – Overview

7 Field Probe Methods

This group of techniques is based on the capacitive coupling principle [26, 27]. These methods are used for surface charge and surface potential measurements. The following subsections describe leading methods which belong to the electrostatic field probe category.

7.1 Static charge detector.

The charge induced on a sensing electrode is measured with an electrometer. This method is very sensitive to fluctuations of the distance between sensing element and examined surface. Reported spatial resolution of 10 [μm] [28].

7.2 Dynamic current sensing.

A current sensing probe is placed close to the investigated surface. As it moves in the direction parallel to the surface, a current is induced. This current is proportional to the capacitive coupling and to the rate of change of the voltage between the sensing element and the surface. This method is very sensitive to changes in the surface-probe distance [26].

7.3 Surface potential probe.

The probe uses a mechanically vibrating sensor for non-contact surface charge and/or voltage detection. The principle of operation is based on the capacitive coupling between the surface under test and the probe sensor (Figure 5). Voltage U1 corresponds to a difference of potentials between the probe and the ground (earth) reference and U2 is the voltage between the charged plane and ground. The voltage U between the sensor and the plate is then equal to |U1-U2|. Assuming that the probe is grounded (so that U1=0 and U=U2), the charge on the tested surface can be calculated as:

$$Q = U \cdot \frac{\epsilon \epsilon_0 A}{D} \quad (7)$$

As long as it is possible to determine the voltage U and U1, the charge on the tested surface can be calculated.

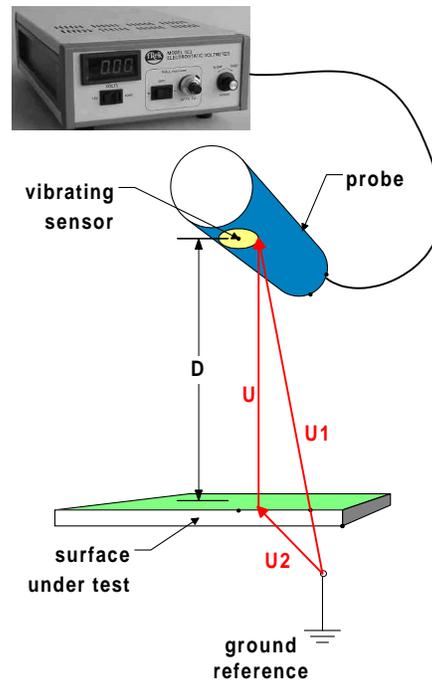


Figure 5: Electrostatic voltmeter - measurement principle.

Any change of the distance between electrodes during the time interval dt requires certain amount of electric charge dQ to be delivered to or taken away from the probe so the voltage U can remain constant:

$$\begin{aligned} \frac{dQ}{dt} &= U \cdot \epsilon \epsilon_0 A \cdot \frac{d}{dt} \left(\frac{1}{D(t)} \right) = \\ &= U \cdot \epsilon \epsilon_0 A \cdot \frac{-\frac{dD(t)}{dt}}{[D_0 + D_1(t)]^2} \quad (8) \end{aligned}$$

where $D = D(t) = D_0 + D_1(t)$. D is a time-dependent function and is comprised of 2 components:

Charge Detection Methods for Dielectrics – Overview

- a constant $D(0)$ representing the separation between electrodes before change of the distance,
- a function $D_1(t)$ describing changes of the distance in time.

In most of electrostatic voltmeter (ESVM) designs the probe is vibrated sinusoidally in the direction perpendicular to the tested surface and the current flowing to and from the probe changes proportionally to the amplitude and frequency of that vibration. The current can be determined as:

$$\begin{aligned}
 I &= U \cdot \frac{dC}{dt} \\
 &= U \cdot \frac{d}{dt} \left(\frac{\epsilon\epsilon_0 A}{D_0 + D_1 \cdot \sin(\omega t)} \right) = \\
 &= -U \cdot \epsilon\epsilon_0 A \cdot \frac{D_1 \omega \cos(\omega t)}{[D_0 + D_1 \sin(\omega t)]^2} \quad (9)
 \end{aligned}$$

In order to nullify the current I the voltage U has to be brought to zero. In this case the probe-to-ground voltage U_1 will be equal to the voltage on the surface U_2 . Therefore it is possible to measure the voltage U_2 by monitoring U_1 using the current $I = 0$ condition. A broad variety of designs for current detection circuitry was proposed in order to improve the quality of surface charge and potential readings [29–38], with Trek’s voltmeters among the leading solutions for scientific and industrial applications. The spatial resolution of the ESVM is limited by the size of the sensing element which is built into the probe. One of the biggest advantages of ESVMs is their ability to measure a broad range of surface charges and voltages without disturbing the state of the measured object.

8 Other Methods

There also exist other methods that can be used for charge distribution detection. For example, there is a family of techniques utilizing Pockels and Kerr effects [39].

¹the refraction of light in an anisotropic material (as calcite) in two slightly different directions to form two rays

8.1 Pockels effect.

The Pockels effect is a linear electro–optic effect often observed in crystalline materials. Under an external electric field applied the birefringence¹ difference Δn is introduced. Its dependence on the electric field density can be expressed as:

$$\Delta n = n_0^3 \cdot \gamma_p E \quad (10)$$

Where n_0 is the refractive index for normal light and γ_p is the Pockels constant of the crystal material [40, 41].

8.2 Kerr effect.

The Kerr effect is a quadratic electro–optical effect and can be observed mostly in dielectric liquids. It has been used widely to measure electric field distributions in dielectric fluids. Some solid materials (i.e. polymethyl methacrylate – PMMA) also exhibit Kerr effect [42]. However, the internal stress resulting from electrostatic forces inside the material also contributes simultaneously to birefringence due to a photoelastic effect. Unfortunately these two effects cannot be separated therefore the use of the Kerr effect for field measurements in solids is limited.

8.3 Spectroscopic measurement.

Spectroscopic tests utilize the fact that spectral lines of the irradiated material are shifted and/or split in the presence of an electric field induced by charges [43].

Another two methods used in the space charge detection are the electron beam probing and diffusing chemical solvent techniques. These methods did not receive much attention because they are destructive and the results are not reliable.

Charge Detection Methods for Dielectrics – Overview

9 Summary

In addition to all methods presented in this paper there are also techniques that are combinations of surface or space charge measurement techniques mentioned here. Choice depends mostly on the kind of material that is to be tested. Any internal defects of the tested medium will have their influence on the measurement results. Many of the techniques described here apply to thin dielectric materials. For measurements of volume charges in thick insulators only the pressure wave propagation and electroacoustic stress pulse methods will give reliable results [44–46]. Aside of reliability of described methods, there is also a problem of repeatability. Most of the methods described in this paper have the major disadvantage of the measure-

ments causing disruption of the state of the material sample. This means that after the measurement is done, the sample is usually discharged, sometimes even altered chemically and physically, therefore the test cannot be repeated under exactly the same conditions. The only way to maintain the original state of the tested material is to use one of the contactless methods. Electrostatic voltmeters that use vibrating electrode probes display very high accuracy and repeatability of measurements. Trek, Inc. specializes in this kind of instrumentation, which, aside of their accuracy and reliability, have also been proven to provide one of the most convenient ways of surface charge and/or surface potential measurements. In summary, Table 1 [44] presents all the methods described in this application note along with their capabilities.

	Method	Disturbance	Scan mechanism	Detection process	Resolution [μm]	Sample thickness [μm]	Comments
1	Thermal pulse method	Absorption of short-light pulse in front electrode	Diffusion according to heat-conduction equations	Voltage change across sample	2	200	High resolution, requires deconvolution
2	Laser intensity modulation method	Absorption of modulated light in front electrode	Frequency-dependent steady-state heat profile	Current between sample electrodes	2	25	Numerical deconvolution required
3	Laser induced pressure pulse method	Absorption of short laser light pulse in front electrode	Propagation with longitudinal sound velocity	Current between sample electrodes	1	100–1000	No deconvolution required.

Table 1: Overview of methods [1]

Charge Detection Methods for Dielectrics – Overview

Table 1, cont.							
	Method	Disturbance	Scan mechanism	Detection process	Resolution [μm]	Sample thickness [μm]	Comments
4	Thermoelastically generated laser induced pressure pulse	Absorption of short laser light pulse in thin buried layer	Propagation with longitudinal sound velocity	Current or voltage between sample electrodes	1	50–70	Deconvolution required.
5	Piezoelectrically induced pressure pulse	Absorption of piezoelectrically generated short pulse in metal target	Propagation with longitudinal sound velocity	Current or voltage between sample electrodes	10	5–200	Resolution improved with deconvolution. Also used for surface charge measurements.
6	Non-structured acoustic pulse method	HV spark between conductor and metal diaphragm	Propagation with longitudinal sound velocity	Voltage between sample electrodes	1000	10000	Used for solid and liquid dielectrics. Higher resolution with deconvolution.
7	Laser generated acoustic pulse method	Absorption of laser light in thin paper target	Propagation with longitudinal sound velocity	Voltage between sample electrodes	50	3000	Deconvolution is required. Target and sample immersed in dielectric liquid.

Table 1: Overview of methods [1]

Charge Detection Methods for Dielectrics – Overview

Table 1, cont.							
	Method	Disturbance	Scan mechanism	Detection process	Re-solution [μm]	Sample thickness [μm]	Comments
8	Acoustic probe method	Absorption of laser light pulse in front electrode	Propagation with longitudinal sound velocity	Voltage between sample electrodes	200	2000–6000	
9	Piezoelectrically-generated pressure step method	Electrical excitation of piezoelectric plate	Propagation with longitudinal sound velocity	Current between sample electrodes	1	25	Deconvolution is required
10	Thermal step method	Applying two isothermal sources across sample	Thermal expansion of the sample	Current between sample electrodes	150	2000–20000	Deconvolution is required
11	Electro-acoustic stress pulse method	Force or modulated electric field on charges in sample	Propagation with longitudinal sound velocity	Piezoelectric transducer at sample electrode	100	10000	Deconvolution is required. Also used for surface charge measurements.
12	Photoconductivity method	Absorption of narrow light beam in sample	External movement of light beam	Current between sample electrodes	1.5	–	Nondestructive for short illumination time.

Table 1: Overview of methods [1]

Charge Detection Methods for Dielectrics – Overview

Table 1, cont.							
	Method	Disturbance	Scan mechanism	Detection process	Resolution [μm]	Sample thickness [μm]	Comments
13	Space charge mapping	Interaction of polarized light with field	Parallel illumination of sample volume or movement of the light beam or sample	Photographic record	200	–	Mostly used on transparent dielectric liquids.
14	Spectroscopy	Absorption of exciting radiation in sample	External movement of radiation source or sample	Relative change in the observed spectrum	50	–	Few applications
15	Field probe	None	Capacitive coupling to the field	Current	200	-	Non-destructive, surface charge tests

Table 1: Overview of methods [1]

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Charge Detection Methods for Dielectrics – Overview

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Charge Detection Methods for Dielectrics – Overview

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