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C. Filloy-Corbrion, C. Boue, E. Géron, T. Ditchi, J. Lucas, et al.. Surface temperature measurement for space charge distribution measurements with thermal methods. *IEEE Transactions on Dielectrics and Electrical Insulation*, 2015, 22 (3), pp.1506-1511. 10.1109/TDEI.2015.7116345 . hal-01629260

HAL Id: hal-01629260

<https://hal.science/hal-01629260v1>

Submitted on 21 Nov 2021

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Surface Temperature Measurement for Space Charge Distribution Measurements with Thermal Methods

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ABSTRACT

The implementation of space charge measurements based on thermal perturbation on thin films requires an improvement of the temperature distribution estimation at the surface and in the depth of dielectric materials for getting reliable space charge profile measurements. Absolute temperature variations are needed, both in time and space. The present contribution addresses surface temperature measurements based on either thermoelectric or bolometric effects. Both responses have been measured on copper-coated silicon nitride layers and gold-coated polypropylene films heated with a Nd-YAG laser pulse. It is shown that high temporal resolution thermal response can be obtained through the bolometric response and that the information appears nearly independent on the nature of the coating electrode. The setup developed provides good signal to noise ratio for heated electrodes of a few ohm resistance. Strategies are still to develop to get the temperature profile in the insulating sample layer.

Index Terms — Space charges, thermal measurement method, spatial resolution, surface temperature.

1 INTRODUCTION

Space charge distribution measurement methods are more and more used for the characterization of insulating material under high voltage. Some of these methods are of particular interest since the charge distribution can be obtained directly, that is to say without requiring an electrical model of the sample under test, and non-destructively, that is to say that measurements can be achieved consecutively. There are mainly three families of such measurement methods. The first family is based on thermal perturbation [1]. In that family, the sample is heated at one interface. The charges displaced by the thermal expansion during the diffusion of heat generate a space-charge-correlated electrical signal. The second family is the pressure-wave-propagation (PWP) method [2] in which a pressure wave is transmitted to the sample. The pressure wave displaces consecutively the planes of charges encountered during the propagation, which generates in turn a space-charge-correlated electrical signal. The third family is the pulse electro-acoustic (PEA) method [3], where the sample is submitted to a high voltage pulse which modifies the force acting on each charge. Space-charge-correlated elastic waves are generated and can be measured by a transducer acoustically coupled to the sample. All these measurement methods are similar in the electrical information they yield [4], but the way they are implemented makes one or the other more appropriate, depending on application conditions.

In terms of spatial resolution, the thermal methods have the advantage of providing the best spatial resolution for a given measurement bandwidth [5]. Heat diffusion is indeed a slow process in comparison to elastic wave propagation. In polymeric materials for instance, a 1 GHz bandwidth is required for 1 μm spatial resolution with the PWP or the PEA methods whereas 10 MHz bandwidth is sufficient for 100 nm spatial resolution with the thermal method. However, the thermal method suffers from the inverse calculation required to recover the space charge distribution from the measured signal. This is due to the evolution of the temperature distribution in the material during heat diffusion [6]. That is known as an ill-posed problem for

which any small errors are greatly magnified by the calculation. One important source of errors stems from the inaccurate estimation of heat diffusion in the tested material. It indeed depends on the thermal properties of the sample, on its thickness and on the material it is thermally coupled to. For a high spatial resolution, as expected in the case of thin film insulators or power integrated circuits, the accurate estimation of the evolution of the temperature distribution in the sample is absolutely required. An accurate surface temperature evolution measurement would thus be of great importance.

In this paper, we show that it is possible to directly measure the surface temperature evolution of the sample under test. In the next section, the surface temperature measurement principle is discussed and presented. The samples, the setup and the measurement protocol are described in the following section. Experimental results are shown and discussed in the last section before conclusion.

2 MEASUREMENT PRINCIPLE

There are various ways for measuring space charge distribution with the thermal method depending on the technique used to produce the heat at the surface of the sample. Heating can be produced using either pulsed [1], continuous [7] or modulated lasers [8, 9], or by directly applying a temperature tank to the sample [10, 11, 12]. In short-circuit measurement conditions, the measured current $i_m(t)$ is expressed as

$$i_m(t) = -C_0 \int \alpha(x) E(x) \frac{\partial \Delta T(t, x)}{\partial t} dx, \quad (1)$$

where C_0 is the sample capacitance at rest, α is a global coefficient taking into account the thermal expansion and the permittivity variation with temperature, $E(x)$ is the electric field and $\Delta T(t, x)$ is the variation of the temperature distribution in the sample. The coefficient α is a constant in the case of uniform materials but may depends on position in the case of laminate samples. Recovering the electric field $E(x)$, hence the space charge distribution, from the signal $i_m(t)$ requires to precisely estimate the temperature distribution variation $\Delta T(t, x)$ at any time t and position x .

For high spatial resolution, high frequency temperature variations are required, hence lasers are preferentially used to heat the sample. Since a heat flux is directly transmitted to the sample, the surface temperature is not known. The temperature distribution ΔT has then to be calculated from diffusion models, assuming most of the time a perfectly defined heat excitation profile, for instance a perfect pulse with instantaneous rise time and fall time. For broadband measurements however, the time during which the actual surface temperature varies is no longer negligible compared to the one of the space charge correlated signal. As a consequence, using a perfect pulse for the heat excitation in the calculation of the temperature distribution in the sample introduces inaccuracies that prevent high spatial resolution to be obtained. It is therefore critical to directly measure the surface temperature instead of assuming it from calculations. Notice that using a calibration procedure consisting in applying a known electric field $E(x)$ in the sample when measuring the signal $i_m(t)$ allows all scaling coefficients to be determined at the same time. As a consequence, it is not necessary to determine C_0 , α and the conversion coefficient between surface temperature measurement and the actual surface temperature. Therefore, only the evolution of the surface temperature is required to improve space charge distribution measurements with thermal methods.

There are various techniques for measuring the surface temperature of an object. Most of the time, infrared sensors are used [13]. They are very convenient because they are contactless, but their response time (frequency range) is not appropriate for high frequency thermal measurements. Moreover, the signal to noise ratio of infrared sensors is relatively small.

Thermoelectric effects, for instance Seebeck's effect used in thermocouples, can be a solution for surface temperature measurements [13]. In that case a voltage proportional to the temperature profile is directly obtained at the heated electrode. Despite the physical contact required with the sample, the sensor bandwidth and sensitivity are sufficient for high frequency thermal measurements. However, specific electrode materials or sample structure are necessary, so this can be an intrusive surface temperature measurement technique for the sample.

Generally used for radiation detection, bolometric effect can also be used for surface temperature measurement [13]. The bolometric detection is based on the variation of the electric resistance of a material with temperature. It mainly originates from the thermal expansion and since the Bridgman constant, which connects the relative volume variation to the relative resistivity variation, is approximately equal to 2 in the case of metals, the bolometric response

is nearly independent on the electrode material. Moreover, the bolometric effect bandwidth is compatible with high frequency measurements [14] and it is a completely controllable effect since the generated signal is proportional to the current flowing through the sample electrode in addition to be proportional to the temperature.

The principle of the bolometric measurement of the surface temperature [15] is to feed one edge of the heated electrode with a current while the other edge is connected to ground as sketched in Figure 1. When the laser hits the sample electrode, the resistance of the electrode varies with temperature and so the voltage v_T across the current supply I_0 . The space charge distribution correlated measurement v_p can be measured at the same time.

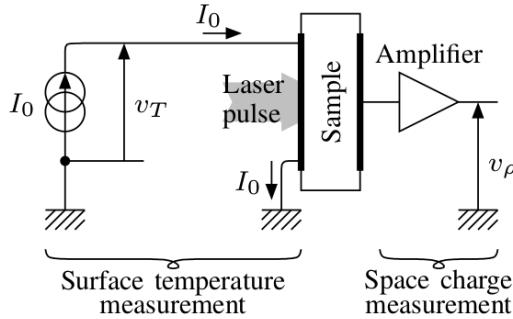


Figure 1. Setup for space charge distribution measurements with the thermal pulse technique including a surface temperature measurement. The voltage v_p is the space charge distribution correlated signal and the voltage v_T is the surface temperature proportional signal.

Because bolometric and thermoelectric responses are measured at the same time, the signal δv_T proportional to surface temperature variation ΔT_0 is

$$\delta v_T = \frac{\partial R}{\partial T} \times I_0 \times \Delta T_0 + \frac{\partial v_T}{\partial T} \times \Delta T_0 \quad (2)$$

The first term stands for the bolometric effect and is proportional to the current I_0 and to the surface temperature variation ΔT_0 . The second term is only proportional to ΔT_0 and gathers all thermoelectric effects. Notice that it is not necessary to consider a precise distribution of temperature on the heated electrode. An average value is sufficient because the temperature in (1) only depends on x , so it is already averaged over the electrode area. The bolometric contribution can be easily isolated from the difference of a signal obtained with a current I_0 and a signal obtained with a current $-I_0$.

3 SAMPLE, SETUP AND PROTOCOL

Surface temperature measurements by bolometric effect have been tested with two different samples. The first sample is composed of a 200 nm thick copper electrode deposited on a 300 nm thick silicon nitride layer itself deposited on a 650 μm thick p-doped silicon wafer. The second sample is composed of a 300 nm thick gold electrode deposited on 200 μm thick polypropylene sample. The heated electrode is approximately 1 cm width in order to reduce the non-heated surface as much as possible in the path of the current I_0 and 2 cm height in order to provide easier connections to the current supply and to the ground. Connections are made through a 500 μm thick high-conductivity silver-containing silicone rubber. The current source is replaced by a stabilized voltage source feeding the heated electrode through a 6.8 Ω resistor. That resistor is sufficiently small to ensure a good sensitivity when taking into account the resistance of the heated electrode, which is of about a few ohms.

Measurements are carried out with a 5 ns duration 1 mJ/mm² energy Nd:YAG laser pulse. The beam diameter is approximately 8 mm, so that almost all the heated electrode width is excited. A typical laser pulse measured by a photo-diode is shown in Figure 2.

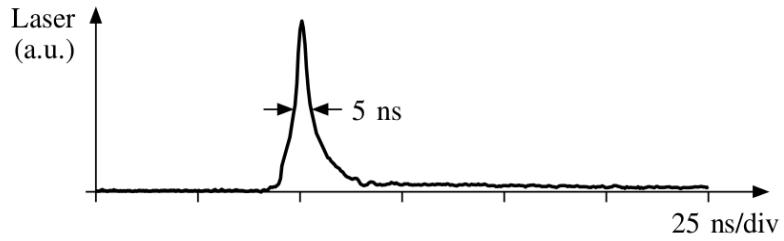


Figure 2. Laser pulse measured by a photo-diode. This is the image of the heat pulse used in thermal measurements.

The bolometric signal is decoupled with a capacitor and amplified by a 40 dB DC to 80 MHz bandwidth amplifier. All measurements are averaged over 8 acquisitions. Each set of measurements is composed of 3 measurements. The first measurement is performed under a positive current. The second measurement is performed under a negative current. The third measurement is performed under zero current. In addition, the 3 first measurements are carried out with the laser hitting the electrode while the electrode is masked from the laser in the 3 next measurements. These 6 measurements make it possible to isolate the bolometric response (differential mode), the thermoelectric response (common mode) and to remove reproducible noise, such as the one produced by the laser switching electronics.

4 EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 shows raw measurements with the gold-coated-polypropylene sample for a positive current when the laser hits the electrode and when the electrode is masked. Because the heated electrode is not directly connected to the ground, a clear electromagnetic coupling with the laser switching electronics is visible in both measurements. But since the electromagnetic coupling is completely reproducible, a simple subtraction is sufficient to remove this spurious coupling. Hereafter, the electromagnetic coupling is subtracted from all signals.

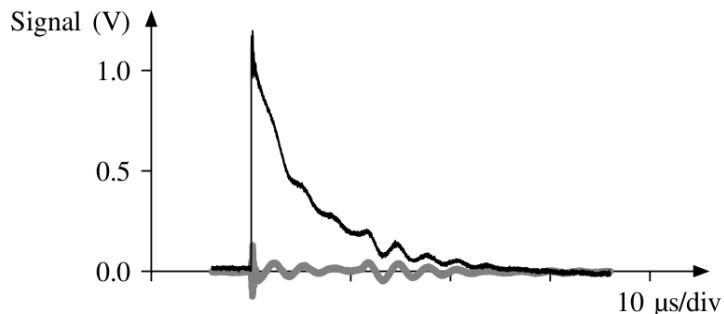


Figure 3. Raw measurements for 50 mA flowing through the gold electrode of a polypropylene material. The laser hits the electrode (black line) or the electrode is masked (gray line).

Figure 4 shows that the signal is clearly dependent on the current flowing through the electrode and thus that the bolometric contribution can be easily detected. Moreover, the signal to noise ratio is sufficiently large to combine measurements together in order to isolate the bolometric effect in one hand and the thermoelectric effect in the other hand.

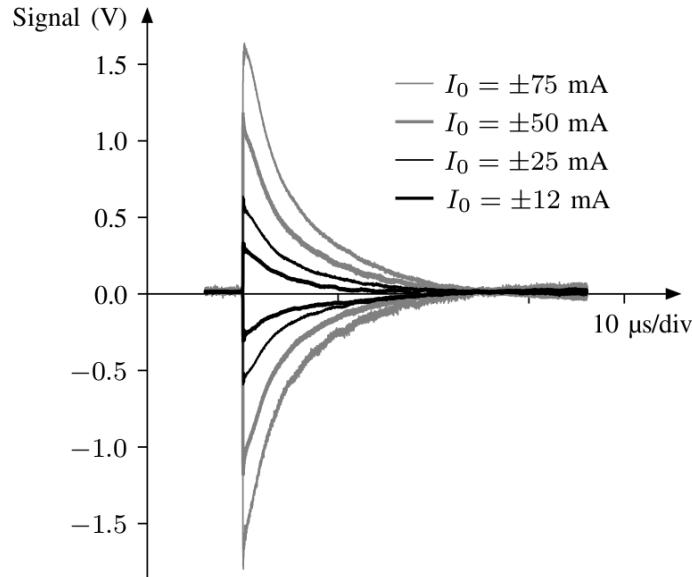


Figure 4. Signals obtained for various currents for the gold-coated polypropylene sample. The dependence of the signal on the current is due to the bolometric effect.

Contrarily to the case of the gold-coated polypropylene sample (Figure 4), measurements are highly non symmetrical in the case of the copper-coated silicon nitride sample (Figure 5). This indicates a large contribution of thermoelectric effect.

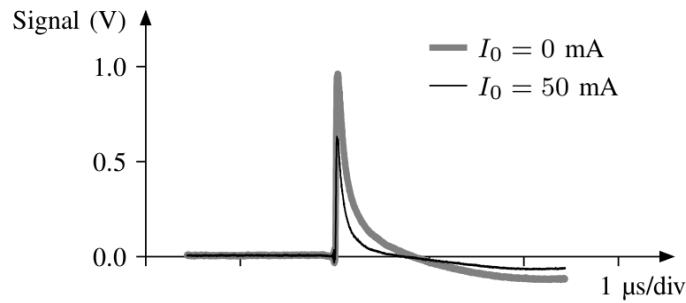


Figure 5. Signals obtained with the copper-coated polypropylene sample at 0 and -50 mA.

The great difference between these two samples is that the copper-coated sample is deposited on p-doped silicon. As a consequence, when heat diffuses into the substrate, it slightly increases the mobile carrier density and thus changes the contact potential [16]. Since silicon nitride layer is only 300 nm thick, heat enters the silicon substrate in less than a nanosecond, therefore explaining the simultaneity of the thermoelectric signal observed.

The subtraction between the signal obtained with a positive current and the one obtained with the opposite current gives twice the bolometric contribution which is proportional to the current. The sum of the signal obtained with a positive current and the one obtained with the opposite current gives twice the thermoelectric effect. The thermoelectric effect can also be obtained from a zero current measurement. Figures 6a and 7a show the bolometric effect of the copper-coated silicon nitride and gold-coated polypropylene samples respectively and Figures 6b and 7b show their thermoelectric effect. As expected in Figure 6 the bolometric and thermoelectric effects have the same profile, since both are due to the same temperature evolution. They also have similar amplitudes though the thermoelectric signal has more noise. In the case of the polypropylene sample however, the thermoelectric signal is much smaller than the bolometric signal, and is almost hidden by the noise. This result illustrates the large variability of the thermoelectric effect which depends greatly on the properties of both electrode and sample structure. On the contrary, the bolometric response is well detected for both samples, the difference in amplitude (a factor 3) could be explained by the difference of the heated electrode resistance and emissivity. This latter parameter depends on the nature of the electrode, its roughness and surface state.

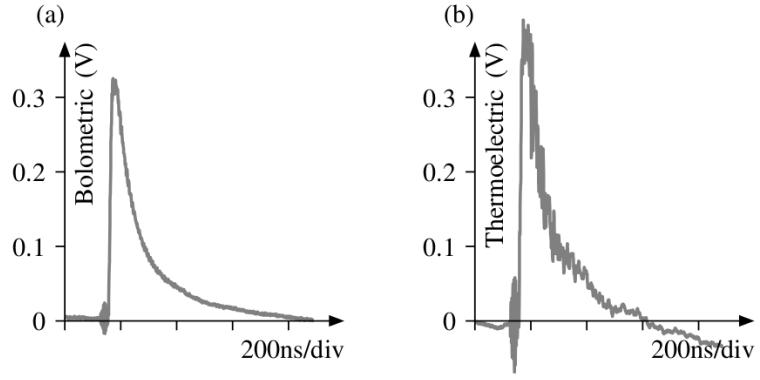


Figure 6. Copper-coated silicon-nitride sample. (a) bolometric effect at 50 mA and (b) thermoelectric effect. Both effects give similar results in terms of shape and amplitude.

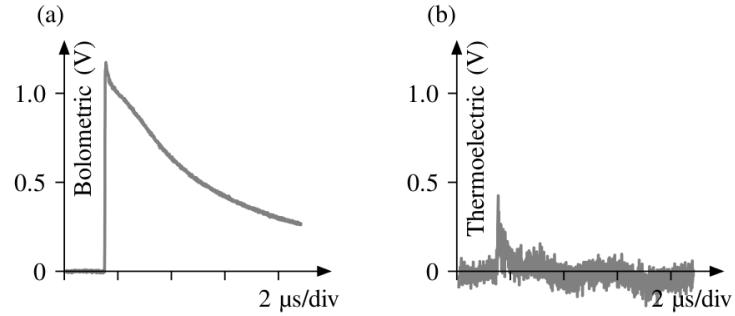


Figure 7. Gold-coated polypropylene sample. (a) bolometric effect at 50 mA and (b) thermoelectric effect. Thermoelectric effect is negligible compared to bolometric effect for this sample.

In terms of temporal response, the rise time of both samples is similar, about 11 ns. The rise time corresponds to the complete duration of the laser pulse which is 5 ns at mid amplitude. The fall time for both samples are however very different. In the case of the silicon-nitride sample, it is about 235 ns whereas in the case of the polypropylene sample it is of the order of 13.6 μ s (see Figure 4 for a longer time scale than in Figure 7). If the samples were uniform semi-infinite materials, the surface temperature due to a heat pulse would be

$$\Delta T(t, x=0) = \Delta T_0 = Q_0(t) \square \frac{1}{m_v c \sqrt{D t}} \square \frac{1}{\lambda} \quad (3)$$

where $Q_0(t)$ is the power density deposited on the sample surface, m_v is the mass density of the sample, c its heat capacity, and D its diffusivity. The operator \square stands for the convolution product. As a consequence, the temperature profile should be similar whatever the material being tested. It is obviously not the case when comparing Figures 6a and 7a. Actually, the samples are not semi-infinite and uniform. Thus, the variation of effusivity, which is the thermal impedance expressed as $\sqrt{t_v c \lambda}$ where λ is heat conductivity, introduces heat flux reflections at the interfaces that modify the temperature distribution and evolution inside the sample. As an example, the decreasing rate of the surface temperature profile in Figure 7a is not constant. That experimental observation can be completely numerically calculated. However, the thickness of the material layers and their diffusivity and conductivity must be accurately known as any small error in any of these parameters would lead to a completely erroneous temperature distribution and evolution, resulting in turn to large errors in the reconstructed space charge distribution. Contrarily to the numerical calculation, the direct measurement of the surface temperature will bring more confidence in the space charge distribution obtained from the signal, since no estimations would be required.

5 CONCLUSION

In this paper, we have shown that it is possible to measure the surface temperature profile with a bolometric effect in the scheme of a thermal setup for measuring space charge distribution. Compared to other effects, bolometric effect has the advantage of producing similar signals whatever the metal being used for the sample electrode. The experimental setup and the measurement protocol described give good signal to noise ratio for heated electrodes of a few ohm resistance.

Obtaining the surface temperature of sample is a key point for improving the spatial resolution of space charge distribution measurement with thermal methods. However, all is not resolved because the surface temperature is only one point in the temperature distribution in the sample. The complete distribution can be obtained by the surface temperature measured at both sides of the sample, for instance by two bolometric measurements, or by an additional calibration measurement. This will be the future step of this study.

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