An Insight into Space Charge Measurements

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Abstract—This paper aims at giving an insight into the field of non-destructive methods for localizing and quantifying electric charges and field distribution in dielectrics. The fundamentals of the influence (or "stimuli") methods used for measuring space charge and polarization distributions in solid insulating structures are first presented. The possibilities offered today by these methods and their fallouts in the domains of dielectric materials, electrical engineering and electronics structures are then put into evidence using various supporting examples. Experimental set-ups and results obtained in recent years are reviewed, and perspectives of evolution of these methods are discussed. Challenges and expected achievements in the near future are brought into focus.

Keywords—Space charge, electric field, dielectric, insulator, non-destructive method

I. Introduction

The development of charge-based or charge-controlled devices needs a perfect knowledge of the amount and of the distribution of the electric charge in the different material layers and at their interfaces. This need is particularly acute when high electric fields establish in the structures during operation, as in electrets, MEMS, devices for controlling micro-fluids in lab-on-a-chip, high-voltage high-current integrated devices, micro-electro-thermal heat sinks for micro components etc.

On the other hand, electrical charge accumulation in dielectrics (or space charge, as it is commonly referred to) can have dramatic effects when uncontrolled. Thus, the electric field induced by the development of space charges is superimposed to the geometrical electric field applied to the material in its usual operating conditions. The resulting value of the field can approach and even exceed the breakdown threshold, leading to an alteration or to the destruction of the material and, as a consequence, to a possible failure of the system in which it is included [1]. The risk is increased when high electric fields are applied to the component, at the interface between different materials, or in the presence of external factors able to induce significant amount of charges in the insulating layers (e.g. radiations). Even without reaching breakdown, the charges accumulated in the insulating layers of a device may provoke malfunction affecting system reliability. This is a critical problem in contexts with considerable economical dimensions and where human security considerations are essential, such as in electrical power transport, airborne and space applications.

Determining the charge density and field values and distributions is therefore an important matter, both for designing efficient sensors and for optimizing dielectric materials and structures. Non-destructive measuring techniques are preferable because the evolution of the charge distribution under real operating conditions can be monitored. This has led to the development, over the last decades, of several non-destructive charge measurement techniques, commonly known as "influence methods" or "stimuli methods" [2]–[16]. These methods are based on the application of a mechanical, a thermal or an electrical stimulus which slightly perturbs the electrostatic equilibrium of the measured sample, giving birth to an electrical or mechanical transient response which allows determining the electric field and charge distributions across the sample.

As they are direct, non-destructive and of potential high resolution, the stimuli methods can bring important information when used alone or in combination to other techniques. Historically, the stimuli methods have been used for a wide variety of electrical engineering applications involving thick insulating layers ($> 100\ \mu$m). This is still a very important matter, with the challenge of being able to determine the real field distribution in full-size structures for high voltage applications. On the other hand, increasing interest is now given to the application of stimuli methods to thin layers ($< 1\ \mu$m) and electronic structures [16], [17], as the classical methods used in micro-electronics are either destructive or of insufficient resolution. Another emerging domain of application is the study of the charge distribution at the interface between solids and liquids, for which there is no direct method of measurement.

In the following of this communication, the fundamentals, the main features and the fallouts of these methods are addressed. Results obtained in different domains are presented, then perspectives of evolution and expected achievements are discussed.

II. Fundamentals

There are mainly two families of non-destructive space charge distribution measurement methods: thermal methods and acoustic methods [2]. The latter are composed of pressure methods and electro-acoustic methods, which both use acoustic waves, but in a different manner, i.e. either as a perturbation

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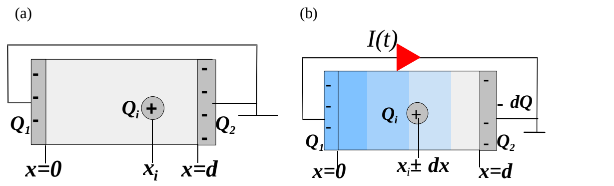

Fig. 1. Principle of a stimulus method (example for a sample in short-circuit). The presence of a space charge Q_i induces influence charges Q_1 and Q_2 at electrodes (a). When the sample equilibrium is perturbed by an external stimulus, charge variation at electrodes ($Q_2 - \mathrm{d}Q$ and $Q_1 + \mathrm{d}Q$, respectively) occurs to restore it. Thus, the transport of charge $\mathrm{d}Q$ from an electrode toward the other through the external circuit results in a current response $I(t) = \mathrm{d}Q/\mathrm{d}t$.

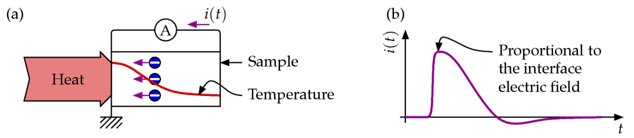

Fig. 2. Principle of thermal methods: (a) Typical set-up: heat diffuses in the sample and slowly displaces the charges. The redistribution of influence charges at electrodes induces in turn an electrical current. (b) Typical signal: with a heat pulse, the amplitude of the signal is proportional to the interface electric field.

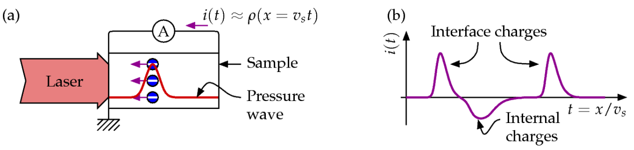

Fig. 3. Principle of pressure-wave-propagation methods: (a) Typical set-up: a pressure wave propagates in the sample and displaces the charges, which induce in turn an electrical current. (b) Typical signal: with a pressure pulse, the signal is an image of the charge distribution; time and position are related through the speed of sound.

or as a probe. All methods are based on the non-homogeneous perturbation of the electrostatic state of the structure under test by an external stimulus. For that purpose, adjacent electrodes are necessary. The tested material (or insulating structure) with its adjacent electrodes is referred herein to as the sample.

The idea lying behind the non-destructive space charge measurement methods is to provoke, with the aid of an external stimulus, a relative displacement of the space charges with respect to the electrodes, and/or a non-homogeneous variation of the permittivity. Indeed, in the absence of the stimulus, on both electrodes of the sample containing a space charge Q_i, influence charges (called Q_1 and Q_2 in Fig. 1) appear owing to the total influence principle. During the application of the stimulus, these influence charges are modified by $\mathrm{d}Q$, resulting in a transient current in the external circuit (if the sample is in short-circuit, as in the figure), or in a transitory modification of the voltage across the sample, if this latter is in open circuit.

Thermal methods use thermal diffusion as the perturbation [3]. The sample is subjected to a low variation of temperature on one of its faces. The diffusion of heat through the insulator expands the material in a non-uniform manner, which slightly displaces the charges. Additionally, the dielectric constant of the material varies locally. Both processes induce an electrical response, either a current between the electrodes in short-circuit conditions or a voltage in open-circuit conditions. That is illustrated in Fig. 2. Different techniques have been developed in order to generate heat diffusion of various time dependences. When pulsed lasers are used, the method is referred to as the thermal pulse technique [4]–[6]. When modulated lasers are used, the method is referred to as the laser-intensity-modulation-method (LIMM) [7], [8]. When alternative thermal waves are used, the method is known as alternative thermal wave method (ATWM) [18]. When temperature steps are used, the method is referred to as the thermal step method (TSM) [9]–[11]. The measured signal is the time derivative of the quantity of influence charges on the electrodes during the diffusion of the thermal wave. Whatever the thermal stimulus, the expression for the electric current is of the form [12]:

$$i(t) = -C \int_0^{\infty} \alpha(x) E(x) \frac{\partial \Delta T(x,t)}{\partial t} \, \mathrm{d}x \qquad (1)$$

where C is the fraction of the sample capacitance corresponding to the heated or cooled area, E the electric field distribution across the sample, α the equivalent linear expansion coefficient which takes into account pyroelectricity, and ΔT is the imposed temperature variation across the sample at every instant. Though the limits of the integral have been extended towards infinity, the electric field has a non-zero value only inside the sample, so the real limits are 0 and d, i.e. the sample limits. As charge density is related to electric field via Poisson's equation $\rho(x) = \varepsilon \mathrm{d}E/\mathrm{d}x$, obtaining the field distribution from Eq. (1) leads to the charge density distribution. Though the thermal methods have been firstly used to simply characterize the polarization homogeneity of pyroelectric films [3], they are now used in a wide variety of applications and thicknesses and many studies have been devoted to estimate the field and charge distributions from the signal [13]–[15], [19].

In the second family (acoustic methods), the pressure-wave-propagation (PWP) methods use elastic wave propagation as the perturbation [20]. An elastic wave is transmitted into the sample. As the wave propagates through the insulator at the velocity of sound, it moves successively the encountered charges. That induces an electrical response which is measurable at the electrodes. This is illustrated in Fig. 3.

One advantage of using an elastic wave is that the short-circuit signal is an image of the charge distribution when using a pressure pulse: the time in the signal is simply the position in the sample divided by sound velocity. Different techniques have been developed in order to generate elastic waves by using shock tubes [21], lasers or piezoelectric materials. When lasers are used [22], [23], the method is referred to as the LIPP method (laser-induced-pressure-pulse). When a piezoelectric transducer generates the pressure wave [24], the method is referred to as the PIPS or the PIPWP methods (piezoelectrically-induced-pressure-step or piezoelectrically-induced-pressure-wave-propagation). In short-circuit conditions, the measured signal has a similar expression as the one of the thermal methods (1), except that α is the equivalent compressibility taking into account the electrostrictive effect and ΔT is replaced by the opposite of

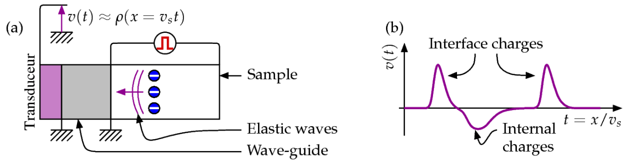

Fig. 4. Principle of electro-acoustic methods: (a) Typical set-up: a voltage variation imposed to the sample changes the force acting on charges which generates in turn elastic waves that are measured by a transducer. (b) Typical signal: with a voltage pulse, the signal is an image of the charge distribution. Time and position are connected through the speed of sound.

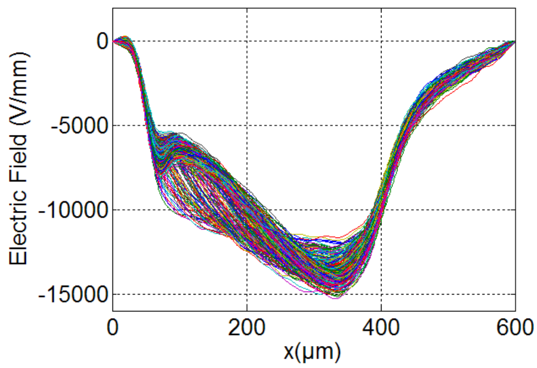

Fig. 5. Evolution of the electric field distribution in a semiconductor/XLPE/semiconductor sample during submission to a 10 kV/mm dc field at 25°C for 15 minutes. Distortion and local enhancement of electric field is observed as a result of charge injection. Data obtained in voltage-on conditions by PEA [30].

the pressure $(-P)$.

The electro-acoustic methods use a fast varying electric stress as the perturbation [25]. The sample is subjected to a fast variation of the voltage applied to its electrodes. This produces a variation of the electrostatic force acting on each charge and thus creates elastic waves propagating from the charges and proportional to their values. These waves travel across the insulator at the speed of sound and can be measured by a transducer (Fig. 4). The measured signal is an image of the charge distribution since elastic waves arrive at a time depending on the distance between the charges and the transducer (the farther the charge, the later the signal). The electro-acoustic method is very similar to the pressure-wave-propagation method, cause and effect just being exchanged. When electrical pulses are applied [25]–[27], the technique is referred to as the PEA method (pulsed-electro-acoustic). When electrical steps are applied [28], the technique is referred to as the SEA method (step-electro-acoustic). The signal obtained with the PEA method is also similar to the one in the thermal methods. The stimulus ΔT is replaced by the pressure waves generated by the charges, these pressure waves having the shape of the electric stimulus. A second contribution to the signal proportional to the square of the electric stimulus exists however, but it can be often neglected or subtracted otherwise.

The above principles hold for any insulating structure, i.e. homogeneous (single-layer) and isotropic samples can be characterized as well as any insulating structure with physical properties varying with the depth-coordinate (multilayers, materials under thermal or field gradient, etc.) If we take the case of a thermal method for an example, Eq. (1) shows that the measured signal is proportional to the overall capacitance of the sample and to the integral of the field multiplied by the α coefficient, which can vary with the depth coordinate with respect to the nature of the different layers composing the structure. Thus, this kind of techniques is fully applicable to multilayer insulating structures or to electronic structures as metal-insulator-semiconductor (MIS) capacitors [16], [17]. Acoustic techniques are also applicable to multi-materials, provided that the reflections of acoustic waves at the interfaces between different materials are taken into account properly [29]. On a larger scale, the presented principles can be used in symmetrical geometry, particularly in coaxial configurations, allowing the stimuli methods to be used on cables and axisymmetric components in general. Finally, the use of adapted setups may allow performing 2D or 3D charge mappings. The possibilities offered today by these techniques are illustrated in the next section.

III. Applications and Features of Stimuli Techniques

A. Flat insulating samples

A large panel of experimental setups on insulating plaques and films has been proposed during the last decade, allowing multiple types of applications through measurements in voltage-on or voltage-off conditions. Some of the most typical ones are presented.

A widespread application of stimuli charge measurement methods is the survey of electric field distribution and space charge build-up in insulating samples submitted to electrical and thermal stress. This is particularly useful for material characterization, material design, process optimization and ageing assessment.

Fig. 5 above shows results obtained by the PEA method on a sandwich composed of an insulating layer (cross-linked polyethylene, XLPE) and two adjacent semiconducting electrodes, submitted to a dc field during several minutes. The figure provides an insight of the field enhancement and distortion caused by charge injection and accumulation which may occur when a dielectric is submitted to a moderate to high dc stress.

Fig. 6 presents space charge distributions obtained by TSM in short-circuit conditions after a long-time submission of semicon-coated XLPE samples to a high ac field, at different temperatures. The effect of the temperature on space charge accumulation in deep traps is put into evidence. Formation of space charge zones at electrodes and in the bulk is shown. In the meantime, the data show that the charge amount does not increase monotonically with temperature (the highest charge accumulation is observed when stressing at 60°C, not at 90°C), bringing into focus that the accumulated charge results from the competition between injection at electrodes and conduction, with specific field and temperature dependencies. On the other hand, a low but non nil charge amount is observed in the

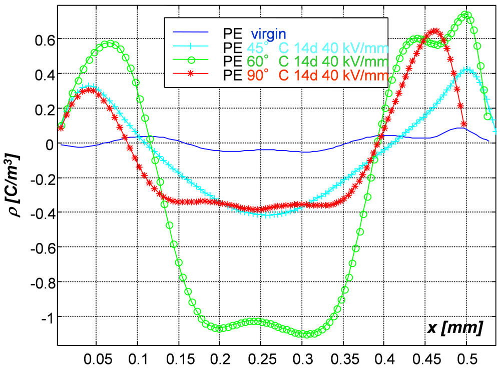

Fig. 6. Space charge distribution in XLPE samples after submission to a 40 kV/mm dc field at 45°C, 60°C and 90°C for 14 days. The presence of a low amount of space charge even without a previous submission to an electric field is shown (virgin sample). Temperature effect on charge accumulation in deep traps (injection/conduction competition) is evidenced. Measurements made in short-circuit by TSM [30].

virgin sample, putting into evidence that some space charge can be present in a material even without previous submission to an electric field, depending on the manufacturing process [31].

The effects of irradiation on insulating films can also be monitored with stimuli techniques [32]–[34]. Such data are useful when testing and studying materials for space applications. Thus, Fig. 7 shows the charge and field distributions obtained by LIMM in a 50 μm gold-coated PTFE sample irradiated with an electron beam. The accumulation of charge near the sample surface during irradiation and its spreading and evacuation after stopping the irradiation can be observed.

Adapted experimental set-ups can allow obtaining 2D and 3D charge or polarization mapping in thin films [15], [35]–[38]. The study of electrets is a typical application. An example is shown in Fig. 8, where TPM and FLIMM have been used to carry out mapping of three-dimensional polarization in a 12 μm-thick PVDF films with the aid of a focused laser mounted on a controlled X-Y translation stage. It is shown in particular that even for such thin samples, inhomogeneities in the polarization can be encountered.

B. Coaxial configuration (cables)

As previously asserted, the principles of the stimuli methods can be used in any geometry, particularly in coaxial configurations, which make them suitable for measurements on power cables. This is of interest for assessing real cable insulation. For the developing sector of HVDC, space charge measurements in cable-like configurations are of significant importance, as the different manufacturing process with respect to flat samples and the existence of a temperature gradient in the insulation of a power cable triggers phenomena that cannot be properly investigated otherwise. Consequently, PEA and TSM-based techniques allowing space charge measurements in cable-like configurations have been proposed.

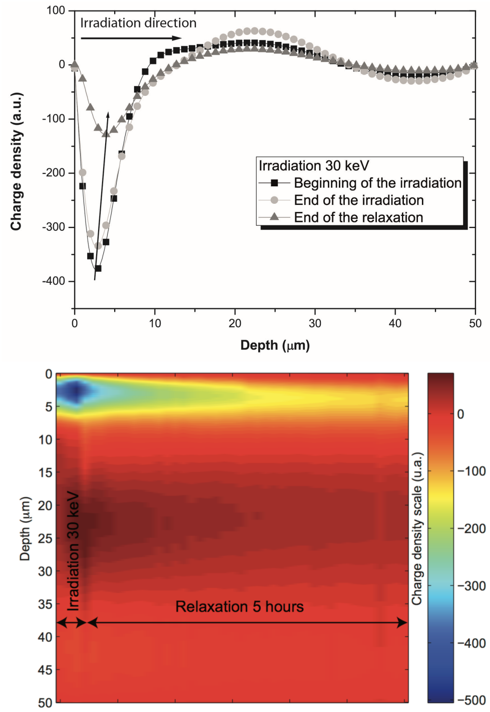

Fig. 7. Electric field and space charge distributions in a thin PTFE sample irradiated with an electron beam of 30 keV. Charge accumulation and relaxation are shown. Measurements made in short-circuit conditions by LIMM [32].

Fig. 9 presents a typical PEA implementation. Variants exist in which the pulse voltage is applied to the conductor at cable end [39]. In the presented example, the measurement cell uses capacitive coupling to apply voltage pulses (dozens of ns, several kV, 400 Hz to 10 kHz) through the outer screen of the cable. HVDC voltages up to several hundreds of kV can be applied on the conductor using dedicated setups [40]. In order to apply a thermal gradient between the cable core and the outer screen, a cable loop heated by a heating transformer is used, allowing measurements under thermal gradient. Examples of space charge profiles measured in a medium voltage cable in voltage-on and voltage-off conditions under temperature gradient are given in Fig. 10. They have been acquired while applying during 90 minutes a 60 kV voltage on the cable core (electric field of 18 kV/mm near the core and of 10 kV/mm near the outer screen), under a temperature gradient of 20°C (70°C on the core and 50°C on the outer screen). The figure allows putting into evidence negative charge build-up occurring in the bulk of the insulation. The method was also applied to probe multilayer insulations in coaxial geometry.

A TSM implementation for power cables is shown in Fig. 11. It allows applying up to 500 kV dc to insulating thicknesses up to 25 mm, under temperature gradients obtained using heating transformers inserted in the cable loop. Two cables are used during the experiments: the studied cable and a second cable, which has the role to compensate the polarization and conduction currents during the space charge measurement.

The TSM measurement cell includes a coaxial thermal diffuser, where the thermal step is created on the outer semicon of the measured cable by the sharp arrival of a cold liquid

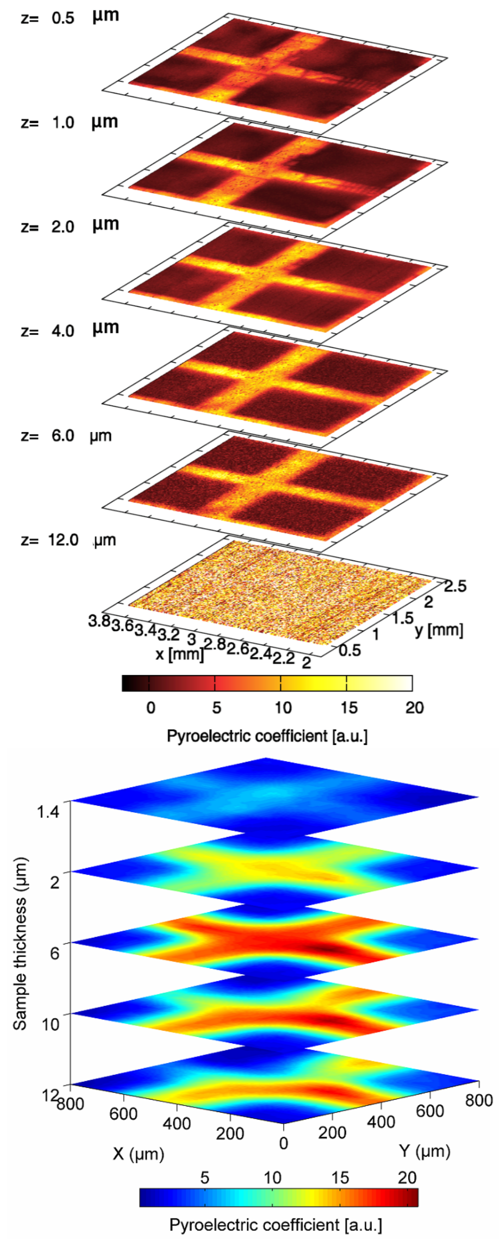

Fig. 8. Polarization maps at different depths z with respect to the surface in 12 μm-thick poly (vinylidene fluoride-trifluoroethylene)) (PVDF-TrFE (65%–35%)) films poled at 70 kV/mm. Measurements made in short-circuit conditions by TPM (top) and FLIMM (bottom) [38].

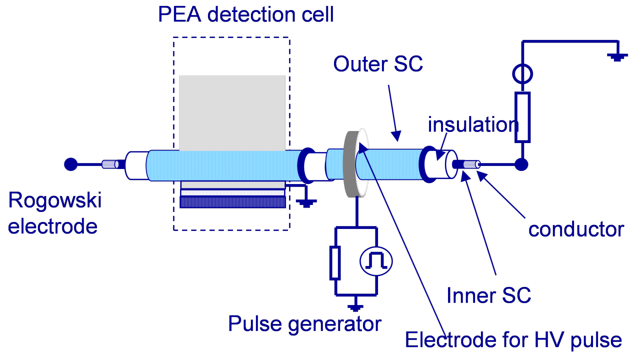

Fig. 9. Diagram of a PEA measurement cell set up for space charge measurements on power cables [30].

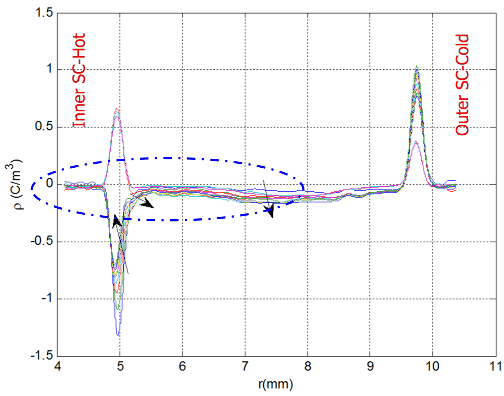

Fig. 10. Space charge measurements by PEA in a medium voltage cable submitted to dc stress (-60 kV) under temperature gradient (70/50°C) [41].

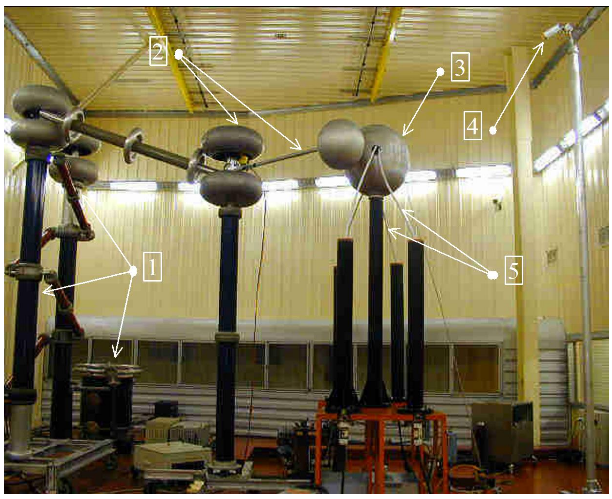

Fig. 11. TSM setup for space charge measurements in HVDC cables. 1: HVDC Supply; 2: Voltage divider and HV switch; 3: cables junction sphere; 4: HV monitoring device (field mill); 5: Cable under test and compensation cable fitted with oil-filled lab terminals [42].

(Fig. 12). The measurement instrument is connected to the compensation cable, which is in series with the measured one during the space charge test. Field and charge profiles, measured in a long-term aged HVDC cable prototype (2600 h) under a temperature gradient of 14°C (80°C on the core, 66°C on the outer semicon) and a voltage of -150 kV (43 kV/mm near the core), are presented in Fig. 13. They show a maximum field distortion after 15 days (up to 80 kV/mm), followed by a smoothing of the electric field distribution up to 105 days under stress. Field distribution may tend toward the purely resistive distribution, but this is far from being obvious even after 105 days testing. Double charge injection at contacts seems to prevail during the ageing campaign, even if negative charge build-up is fading whereas positive charges are progressing toward the bulk of the insulation. Thus, as a key result of this investigation, maximum field distortions and space charge levels are observed after 10–15 days ageing. Beyond

Fig. 12. Thermal diffuser (400 mm long) used to generate the thermal step from the outer screen of a cable [42].

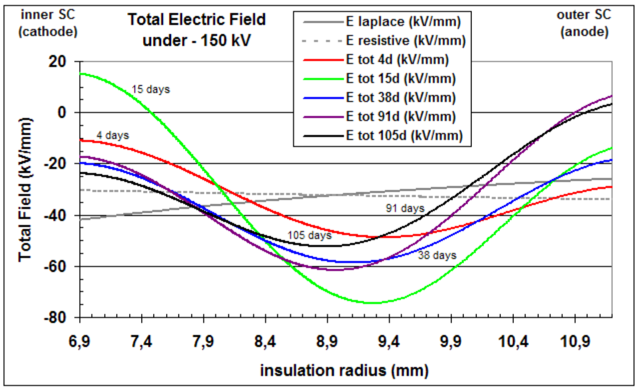

Fig. 13. Electric field distributions obtained by TSM in a cable during long-time dc conditioning under thermal gradient. Capacitive and resistive (steady state) distributions included for comparison [42].

this duration, the distortions are getting weaker, as negative charges start to be evacuated or recombined and positive ones are building up.

It must be underlined that information such as that illustrated in the above examples constitutes a significant input for insulation design and assessment of the behavior of HVDC equipment, which requires a high degree of reliability, and can be obtained only by direct measurement with stimuli methods.

C. Microelectronic structures

If we take the case of a thermal method for an example, Eq. (1) shows that the measured signal is proportional to the overall capacitance of the sample and to the integral of the field multiplied by the α coefficient, which can vary with the depth coordinate with respect to the nature of the different layers composing the structure. Thus, the technique is fully applicable to electronic structures as metal-insulator-semiconductor (MIS) capacitors. In the case of a metal-oxide-semiconductor (MOS) structure for which the composition is shown in Fig. 14, the measured signal $i(t)$ will carry information about the position and the amount of charges contained in the insulating oxide, in the semiconductor and at the interface between the two materials.

Typical dimensions of MOS structures are of the order of nanometers to microns for the oxide and of several hundreds of microns for the doped semiconducting layer (substrate). In order to study phenomena related to reliability and ageing of such components and for designing new structures, it is important to be able to locate as precisely as possible the electric charges within the oxide and at the oxide/semiconductor interface. Indeed, the charges accumulated in the insulating

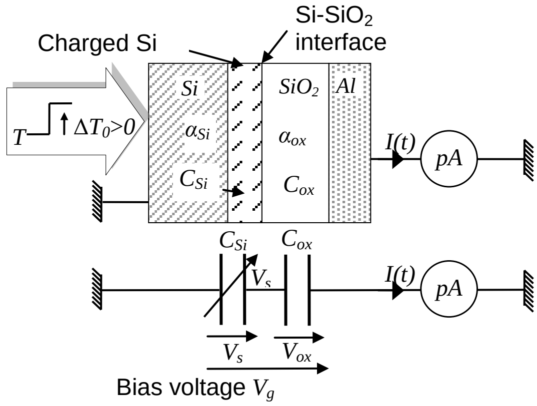

Fig. 14. Thermal method applied to a metal-oxide- semiconductor (MOS) structure. The measured signal is the derivative of the influence charge with time, providing information on the oxide and semiconductor charge [16], [17].

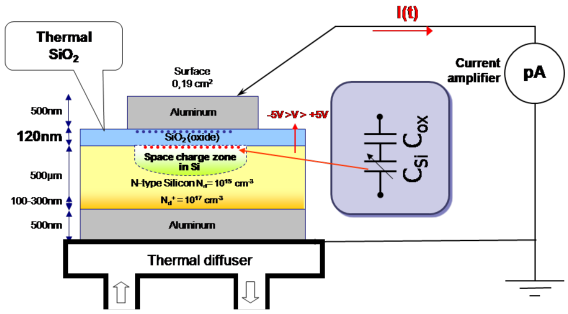

Fig. 15. Experimental set up for thermal step measurements on a MOS structure [16], [17].

layer and at the interface may provoke malfunction of the component even if the insulating layer does not break down. The classical methods used in micro-electronics are either destructive (etch-off technique) or of insufficient spatial resolution (only the charge close to the substrate can be assessed by the capacitance-voltage method). Determining the doping profile in the semiconductor is also of interest for improving manufacturing. In all these fields, significant progress can be made through the use of stimuli methods.

Interesting information on the charge within such a structure can be obtained relatively easily by using a low thermal stimulus of several degrees [16], [17]. Fig. 15 shows such a setup where a thermal stimulus is applied with the aid of a liquid circulating in a radiator in contact with the measured sample (TSM). The signals measured for different voltages applied to the structure V_g are shown in Fig. 16: it can be seen that a characteristic signal is obtained for a given voltage, as the semiconductor is driven into accumulation, depletion or inversion regime. The $I(V_g)|_{\text{Max}}$ data can be plotted to obtain a characteristic of the structure (Fig. 17), then by combining it with low frequency capacitance-voltage measurements one can obtain the total charge of structure and the charge characteristics to the oxide and the interface (Fig. 18).

Complete components, like trench-gated IGBT, can be characterized in such ways in order to assess the evolution of the

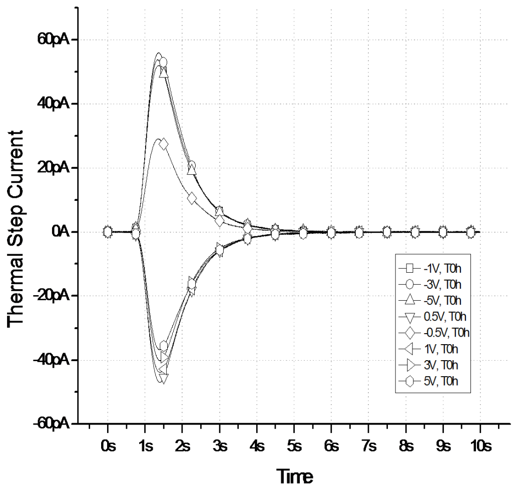

Fig. 16. Typical TSM signals measured for different voltages V_g applied to a MOS sample [16].

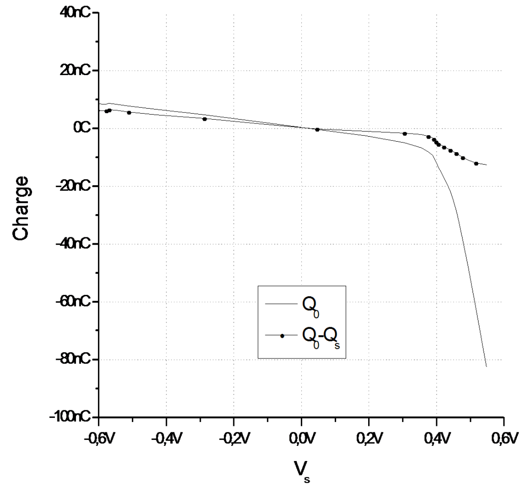

Fig. 18. Total charge of the MOS structure (Q_0) and oxide + interface charge ($Q_0 - Q_S$) versus substrate potential V_S.

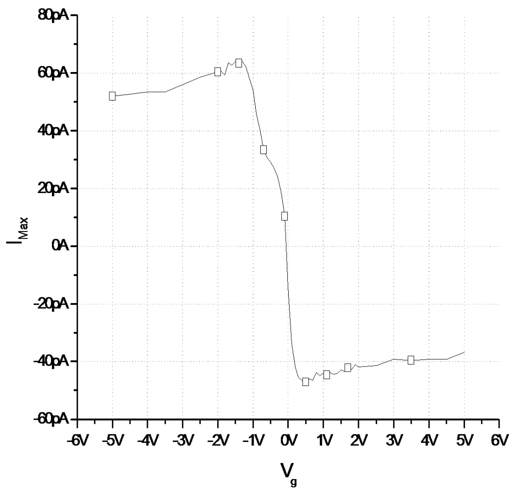

Fig. 17. Maximum of the measured thermal step currents I_{Max} from Fig. 16 plotted versus the gate voltage V_g.

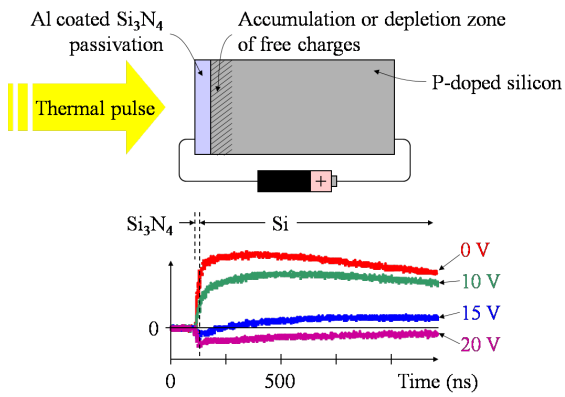

Fig. 19. TPM applied to a metal- insulator- semiconductor (MIS) structure and transient voltage signals measured for different voltages applied to the sample [45].

electrical state of the oxide [43]. It is worth to mention that, in general, the sensitivity of the thermal methods is at least one order of magnitude above that of the capacitance-voltage method, thus allowing putting into evidence changes into the electrical state of the insulators that cannot be observed otherwise [17], [44].

To reduce side effects, the heat flux must be concentrated as much as possible in the gate area. One way to achieve this is to provoke the thermal perturbation by a non-contact method, for instance by using a laser pulse, i.e. using the TPM. This also presents the advantage of diminishing the thermal inertia of the system, thus allowing tending toward much higher resolutions. An example of such a measurement made on a MIS structure composed of 300 nm-thick Si_3N_4 coated on a 10^{18} cm^{-3} *p*-doped Si substrate is shown in Fig. 19. The thermal stimulus was generated with 0.4 mJ – 50 ps laser pulses. In this case, the acquired signal contains more information on the electric field distribution across the oxide and the substrate, as the sampling period is much closer to the transit times of the thermal wave across the two layers: provided that the temperature diffusion through the sample is accurately known, such measurement can allow to closely approach the electric field distribution in the sample.

PWP methods can also be used to study microelectronic components as Schottky diodes, PN diodes and MIS structures. Similarly to the thermal methods, the spatial resolution obtained with the setups used is presently not sufficient to resolve the fine structure of the charge distribution at an interface. The whole charge quantity is determined instead but that already brings more information than the capacitance-voltage measurement technique. An example of measurements carried out with the same structure as the one of Fig. 19, except that the pressure wave is transmitted from the Schottky side

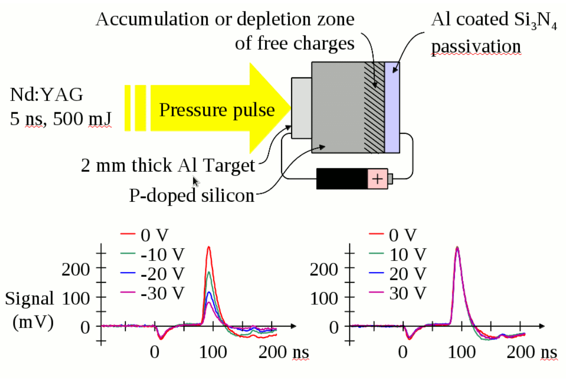

Fig. 20. LIPP method applied to a MIS structure and transient voltage signals measured for different voltages applied to the sample [46].

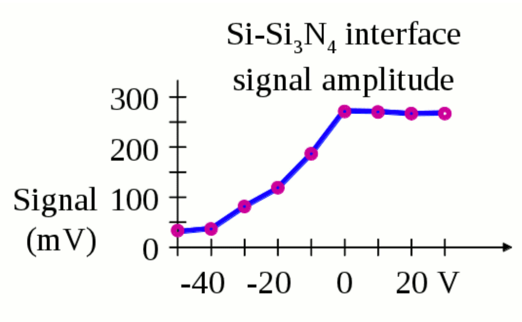

Fig. 21. Amplitude of the MIS interface peak as the function of the applied voltage [47].

of the sample as illustrated in Fig. 20, is given in the latter.

The PWP signal presents two clear peaks, the first being the signature of the Schottky interface and the second the one of the MIS interface. Discerning the two interfaces is already a great improvement compared to the capacitance-voltage technique. With the applied voltage variation, charge variation occurs mainly at the MIS interface. Plotting the amplitude of the second peak as a function of applied voltage leads to similar results than the one found with the thermal methods (Fig. 21), as shown in Fig. 14. Note however that the voltage is applied in the opposite way in the two figures.

The above examples put into evidence that measurement methods usually implemented for thicker materials give interesting new information in the case of electronic structures. However, mainly the overall charge quantity could be accessed so far with such methods, and the details of the distributions remain elusive. Full access to the charge and field repartitions requires an increase in the resolutions, which is one of the challenges to be overcome in the near future.

D. *Synthesis of the features of the stimuli methods*

Although the described families of methods are similar in the information they can provide [2], their implementation is complementary. Consequently, choosing one of them for a particular application depends on the targeted thickness, the targeted resolution, the acceptable duration of the measurement and of the signal-to-noise ratio, as well as on the degree of sophistication of the needed equipment.

Thus, thermal methods provide high sensitivity and a good spatial resolution close to interfaces without requiring wide bandwidth measuring systems. However, far from the interfaces the spatial resolution decreases owing to the physics of thermal diffusion. Methods as LIMM and TPM are well-suited for thin samples (dozens of microns and below), where they can provide resolutions of the order of the micron near the electrode where the thermal stimulus is applied, but the low amount of heat available limits their use for thicker samples. The TSM can be used on much higher thicknesses, as there is theoretically an infinite amount of energy available from the stimulus. The TPM is a fast method (the signal duration is of the order of the μs), while TSM signals last from several μs to several minutes and LIMM characterization requires durations of the order of several dozens of minutes.

Pressure-wave-propagation and electro-acoustic methods give a similar spatial resolution throughout the thickness, but require wide bandwidth measuring system and their sensitivities are usually one order of magnitude lower than for the thermal methods. In turn, their fast response (μs) allows analysis of rapidly varying phenomena. Thermal and pressure-wave-propagation methods have good signal to noise ratios, and therefore can be used for thick samples (e.g., up to 30 mm and above for the TSM). Electro-acoustic methods provide a better decoupling between signal and electric stress and therefore can be safely used under fields close to electrical breakdown situations.

IV. Recent Achievements and Challenges

There is today a growing interest in setting up techniques able to supply high and very high spatial resolutions, especially in view of closely studying interface phenomena and very thin structures. The best resolutions achievable at the present time are of the order of 1 μm for the thermal methods and of 5 to 10 μm for the acoustic methods. Obtaining higher spatial resolutions requires a significant increase of the bandwidth of both the perturbation and the detection set-up. Indeed, spatial resolution is closely related to bandwidth since time and space are connected through diffusion or propagation process [48]. It must also be kept in mind that, whatever the method, the resolution increases with the decrease of the thickness and the increase of the stimulus magnitude. Thus, submicronic resolutions can be reachable only on very thin samples (< 50 μm). However, increasing the resolution in thicker structures (> 100 μm) is also of interest, as the homogeneity degree of such structures is generally higher than 1 μm due to the manufacturing process.

Though the noise level should be taken into account to determine the reachable spatial resolution, the direct resolution is roughly given by $(Dt)^{1/2}$ in the case of thermal methods (D is the thermal diffusivity of the sample and t is the time) and by $v_s t$ in the case of electro-acoustic methods (v_s is the sound velocity). In the case of the thermal methods, $(Dt)^{1/2}$ represents the position for which the temperature variation is half the one at the interface. D is of the order of 10^{-7} m^2/s in polymeric materials and of the order of 10^{-6} m^2/s in silicon dioxide. Therefore, a resolution below 100 nm in

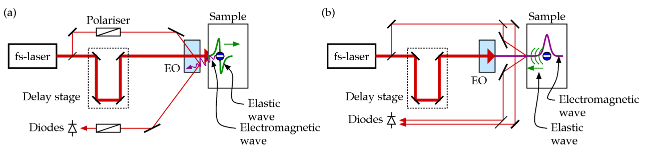

Fig. 22. Principle of thermal methods with femtosecond laser pulses. A pump beam perturbs the sample. The induced charge displacement generates an electromagnetic wave which is measured by electro-optic (EO) sampling. A delay stage provides the time sweep.

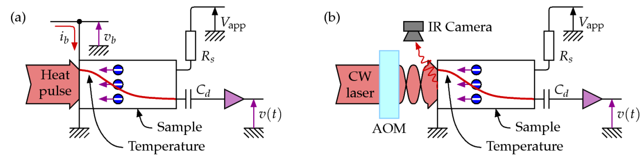

Fig. 23. Experimental set-up proposed for very high resolution thermal method with heat pulse technique [49]. The sample is under voltage and the surface temperature is measured by bolometry. For that purpose, a continuous current flows through the heated electrode and the voltage appearing is measured.

organic layers and components requires a bandwidth higher than 10 MHz, whilst the bandwidth needed for oxides is of the order of 0.1 to 10 GHz. In the first case, nanosecond thermal pulses are required, while femtosecond pulses are needed in the second case. Conventional heaters or pulse generators are no longer adapted and the bandwidth of the usual measuring instruments is not sufficient. New kinds of implementation are required.

Tests where the thermal perturbation is produced by a femtosecond laser pulse in a thin sample have been carried out [49]. When charges are perturbed by heat or by the elastic waves, they emit an electromagnetic wave which can be measured by electro-optic sampling (Fig. 22). Though a spatial resolution better than 50 nm in silicon dioxide could be expected, which is equivalent to 22 nm in polymeric materials, the signal to noise ratio is very poor and obtaining convincing results is still a long way to go with all optical instrumentation.

The technology for obtaining spatial resolutions below 100 nm is therefore at reach, although requiring dedicated equipment such as wide bandwidth acousto-optic modulators for heat excitation. Though most of the needed instruments are now available, reaching the proposed goal remains a challenge, as several experimental and theoretical problems must be solved.

First of all, the perturbation needs to be correctly applied and the signal must be detected above the noise. Measuring the signal is however not sufficient to accurately estimate the charge distribution with the thermal method. Indeed, results drastically depend on the boundary conditions applied in the deconvolution calculations. The simultaneous measurement of the signal and of the interface temperature is of great help, as it allows accessing directly to the stimulus and thus increases the calculation precision for temperature distribution across the material. The feasibility of bolometric measurements from the heated electrode have already been demonstrated [50], but care must be paid to the experimental set up, in particular to the terminals for limiting additional load capacitance and noise increase (Fig. 23).

As the thermal "wave" applied to the electrode attenuates while it diffuses toward the sample bulk, the resolution decreases with the distance from the thermally excited electrode. To increase the bulk resolution, it is then necessary to increase the amount of heat transferred to the sample. For analyzing thicker samples, or if thick electrodes are used (e.g., semicon electrodes), the use of a temperature step is preferable, as the amount of heat supplied to the sample is then virtually infinite. This can be achieved with a fluid at a given temperature. In this case, the challenge relies in optimizing the thermal transfer between the fluid and the sample in order to increase the measurement dynamics as much as possible. Recent studies have shown that resolutions of the order of 1 μm and below can be theoretically reached with such a setup in 100 μm-thick insulating samples provided with 30 μm-thick semicon electrodes [51].

Whatever the form of the thermal stimulus, obtaining the precise amplitude of the thermal excitation by direct measurements is not really useful, since calibration procedures can be used to scale the signal amplitude [11]; only the time evolution of the temperature is required in order to perform the mathematical deconvolution of the Eq. (1), which is a Fredholm equation of the first kind. However, a problem which must be addressed is the improvement of the temperature matrix conditioning, either by mathematical techniques or by the adaptation of the thermal stimulus (boundary conditions), allowing to obtain a less ill-posed inverse problem. A significant work concerning thermal and signal analysis must therefore be performed for improving signal deconvolution.

In the case of the acoustic methods, the resolution is determined by the stimulus width, and for the PEA, by the thickness of the acoustic actuator [52]–[54]. The classical PEA apparatus, with a 5 ns-short duration pulse and a Poly(vinylidene fluoride)–PVDF–piezoelectric sensor of 9 μm-thick, allows electrical characterization of the order of 200 to 500 μm-thick dielectric materials by measuring the spatial and temporal evolution of internal charge distributions with a spatial resolution of about 10 μm. In order to improve the spatial resolution, it is necessary to reduce the piezoelectric sensor thickness and the pulse duration. According to the discerning resolution criterion [55], two planes of charges can be distinguished when they are spaced by a minimum distance of 2.1 μm when using a 1 μm thick piezoelectric sensor and a ns-short duration pulse.

Increasing the spatial resolution requires a bandwidth increase as formerly shown. Since the velocity of sound is about 2000 m/s in polymeric materials, obtaining resolutions as high as 100 nm requires a 10 GHz bandwidth. Until now, pressure-wave-propagation and pulsed-electro-acoustic methods have been implemented with wide bandwidth stimuli such as pulses. But for a 10 GHz bandwidth, the power required to generate a significant signal is too important. The overcome is to use continuous wave stimuli at different frequencies. One great advantage of such stimuli is that electrical matching can be used to drastically improve the coupling coefficient and thus

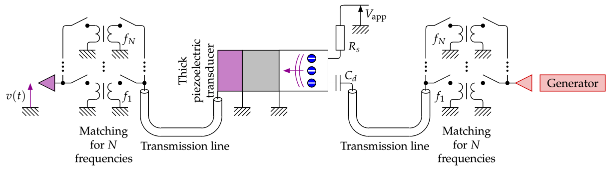

Fig. 24. Experimental set-up proposed for very high resolution pulsed-electro-acoustic or pressure-wave-propagation methods. Matching circuits at the generation and measurement sides are used to optimize the power transfer and thus the signal to noise ratio.

the signal level.

Such a scheme is presented in Fig. 24 in the case of the pulsed-electro-acoustic method or, one should say, the modulated-electro-acoustic method. A generator produces a continuous electric wave at a given frequency which passes through a matching circuit in order to optimize the energy transfer to the sample. Elastic waves generated by the charges travel through the sample and a wave-guide to reach a high frequency transducer. Here again, a matching circuit is used to measure the signal response with an improved signal to noise ratio. The procedure is repeated at various frequencies from 100 MHz to 10 GHz in order to reconstruct the space charge distribution signal from its spectrum. The same scheme can be used for the pressure-wave-propagation method by simply using the generator at the transducer side and the sample at the measurement side.

In these schemes however, coupling is a key parameter since it is necessary to transmit very short duration elastic waves from one material to another. Since it is admitted that an interface is transparent if its thickness is smaller than 1/20 of the smallest wavelength, the interface needs to be roughly better than 5 nm to reach 100 nm spatial resolution. Moreover, the elastic wave must not diffuse on any impurity once transmitted into the material. This requires, in addition, that the used material must be sufficiently pure, such as crystals. A work around can be a measurement of the electro-mechanical conversion energy when the stimulus is applied as recently proposed [56]. In that case, the response of the material is measured from the energy of the stimulus which is not converted. This simplifies the material couplings and the measuring setup, but requires to uncouple a small signal from a large one.

On another level, the increasing interest for HVDC transmissions led to a demand of on-site space charge measurement installations, able to be used in voltage-on conditions directly on components with thick insulating layers like HVDC cables. The challenges encountered in this field are related mainly to the attenuation of the stimulus in very thick samples and to the influence of the HVDC environment. Recent work reported PEA and TSM implementations able to be used on full-size HVDC cables with insulating thicknesses up to 30 mm [57], [58]. This kind of space charge probes are now being used during HVDC cable prequalification ageing tests (Fig. 25) and could be key tools in the development of future extra high voltage transmission apparatus (up to 800 kV).

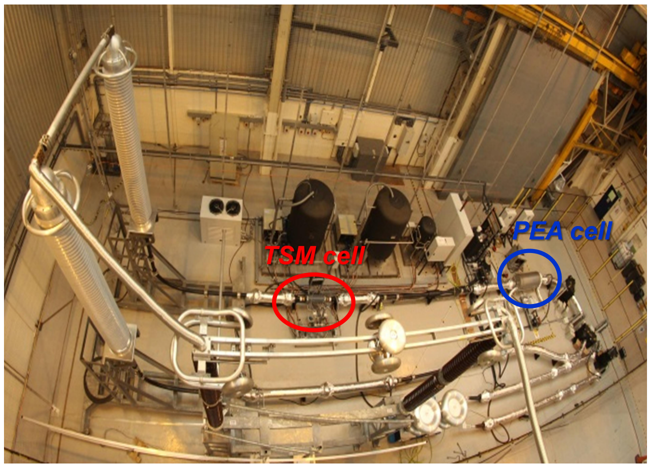

Fig. 25. Full-size HVDC cable loop set up for a prequalification ageing programme, including TSM and PEA cells for space charge measurements [57].

Finally, one interesting way to explore using the direct stimuli space charge measurement techniques is the domain of dielectric liquids. Thus, when a liquid dielectric is put into contact with a solid wall, an electrical double layer (EDL) containing charges of opposite sign appear at the solid/liquid interface. Many studies have been made to measure the EDL charge, but its theoretical distribution has not been confirmed experimentally yet, as so far there has been no method allowing direct measurement of space charge profiles in dielectric liquids. This is where direct space charge measurement methods can bring significant information. Latest developments have demonstrated the feasibility of using a thermal stimulus to analyze the solid/dielectric interface field [59]. Although further developments are still to be made both at the theoretical and experimental level, the obtained results are encouraging in the perspective of new fallouts for stimuli methods.

V. Conclusions and Prospects

Lying on the principle of using low external stimuli to perturb the equilibrium of insulating samples or structures, the direct, non-destructive space charge measurement techniques have been continuously developed for the last three decades to determine and monitor electric field and charge distributions in a wide panel of solid dielectrics of various thicknesses submitted to multiple types of stress (electrical, thermal, radiative). Their use is now being extended to microelectronic structures, full-size components for electric power transmission and liquid dielectrics.

High resolutions down to the submicronic level are now at reach. They will hopefully allow in the next decade to study very thin samples, solid/solid and solid/liquid interfaces. This will undoubtedly contribute to increase the understanding and control of the physical mechanisms which govern charge transport and trapping, and open the way to new applications in the domain of electrical engineering and electronics.

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