CHARGE MEASUREMENT

A charge is one of the fundamental quantities of electricity for which the unit is C (coulomb). One C is the total charge delivered by a current of one A for one second. Although it is generally difficult to measure the quantity and distribution of charges, they are measured by converting the charge quantity into voltage, current, light, or sound. The movement of a charge generates current and electromagnetic waves. This section, however, describes how to measure a static charge.

Here is a simple example of a parallel plate. When x is the position in the depth direction of the sample, the internal static charge $\rho(x)$, electric field $E(x)$, and potential $V(x)$ have the following relationships:

$$E(x) = \int \rho(x)\,dx/\epsilon_0\epsilon_r \quad (1)$$

$$V(x) = -\int E(x)\,dx \quad (2)$$

Thus electric field and potential distributions are calculated by obtaining the charge distribution. For a capacitor whose capacitance is C(F), a simple example, the unknown charge quantity is obtained by measuring the potential difference as

$$Q = CV \quad (3)$$

TOTAL CHARGE MEASUREMENT

The Faraday cage is useful for measuring the total charge of an electrified material. As shown in Fig. 1, the cage has two baskets insulated from each other, and the sample is put in the internal basket. An integrated circuit with an operational amplifier is connected to both baskets. The capacitor of the integrated circuit stores the same amount of charge as the sample. The total charge quantity is measured by Eq. (3), where C is the capacitance and V is the output voltage of the integrated circuit.

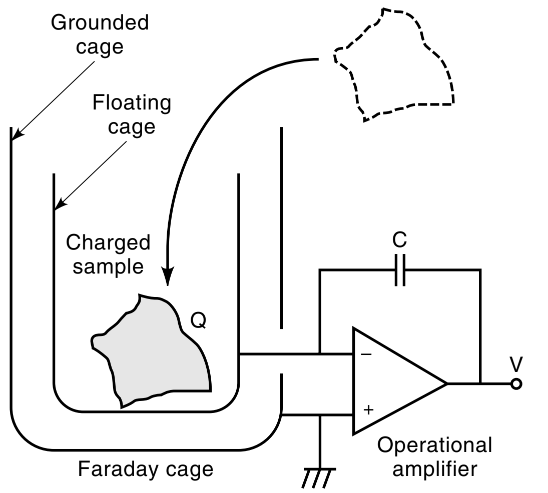

Figure 1. Total charge measurement by a Faraday cage.

SURFACE-CHARGE MEASUREMENT

Potential Probe Measurement

The surface charge of a triboelectrified sample is measured by detecting the surface potential. When the sample is a uniform plate, such as a plastic film, the capacitance per unit area should be constant, and the surface potential is proportional to the surface-charge, based on Eq. (3). The surface charge distribution is observed by detecting the surface potential. This is done by scanning the surface with a probe of a surface potential meter, as shown in Fig. 2.

Electro-Optical Surface-Charge Measurement

Figure 3 shows direct surface-charge measurement without scanning the surface. This optical measuring system uses a crystal in which an electro-optical effect occurs, for example,

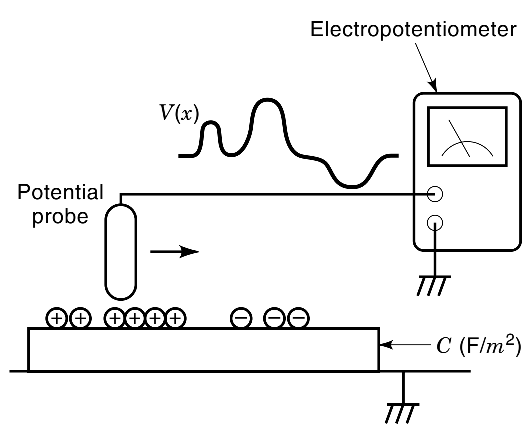

Figure 2. Surface-charge measurement. The charge distribution can be observed by detecting the surface potential with a potential meter probe.

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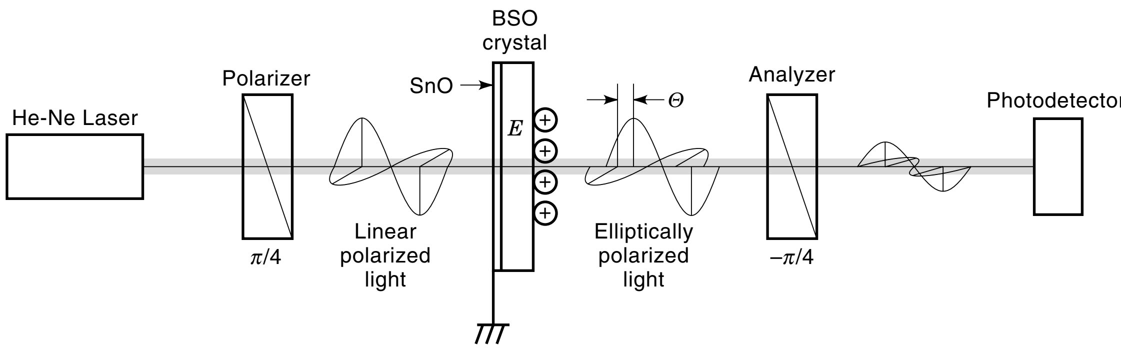


Figure 3. Direct surface-charge measurement without scanning the surface. This optical measuring system uses a crystal which produces an electro-optical effect.

BSO : $Bi_{12}SiO_{20}$ or BGO : $Bi_{12}GeO_{20}$. When a charge accumulates on the surface of the crystal, an electric field is generated inside it. Because of the electric field, the crystal has birefringence, and so the linearly polarized light incident on the crystal becomes elliptically polarized light with retardation θ and permeates an analyzer. The intensity of the incident light I_0 and permeated light ΔI have the following relationship:

$$\theta = K\sigma \tag{4}$$

$$\Delta I/I_0 = \sin^2(\theta/2) \tag{5}$$

where K is the Pockels constant of the crystal, which is determined by the thickness, dielectric constant, and wavelength of the light and σ is the surface-charge density on the crystal. Thus, surface charge distribution is obtained by measuring the distribution of ΔI with a photodetector. When θ is small, however, it is difficult to measure the real surface charge because insignificant leakage light generates an output signal even if there is no surface charge. In this case, a two-dimensional lock-in amplifier is used to measure the real surface charge (1). The lock-in amplifier modulates the signal to be measured and detects the synchronized component with the modulation period. Because this equipment detects very small signals, it is widely used in scientific research. The two-dimensional lock-in amplifier is an example of its application for detecting two-dimensional signals, such as images. Figure 4 shows a measurement system. The incident light is phase-modulated by applying a square voltage to an optical phase modulator made of BSO or other crystals that produce an electro-optical effect. Then, retardation θ becomes one of the following two values, alternatively:

$$\theta = K\sigma + \Delta\theta \text{ and } K\sigma - \Delta\theta \tag{6}$$

Then we calculate the difference between light intensity $\Delta I'$ in the case of $\theta = K\sigma + \Delta\theta$ and $K\sigma - \Delta\theta$. Because the same amount of leakage light exists in each case, the difference is independent of the leakage light and is given by

$$\Delta I'/I_0 = \sin(K\sigma)\sin(\Delta\theta) \tag{7}$$

Assuming that $\Delta\theta$ equals $\pi/2$, then $\Delta I'$ indicates the surface-charge distribution directly when the charge density σ is low. A two-dimensional lock-in amplifier is used to store the difference of two synchronized images in a computer. Averaging a

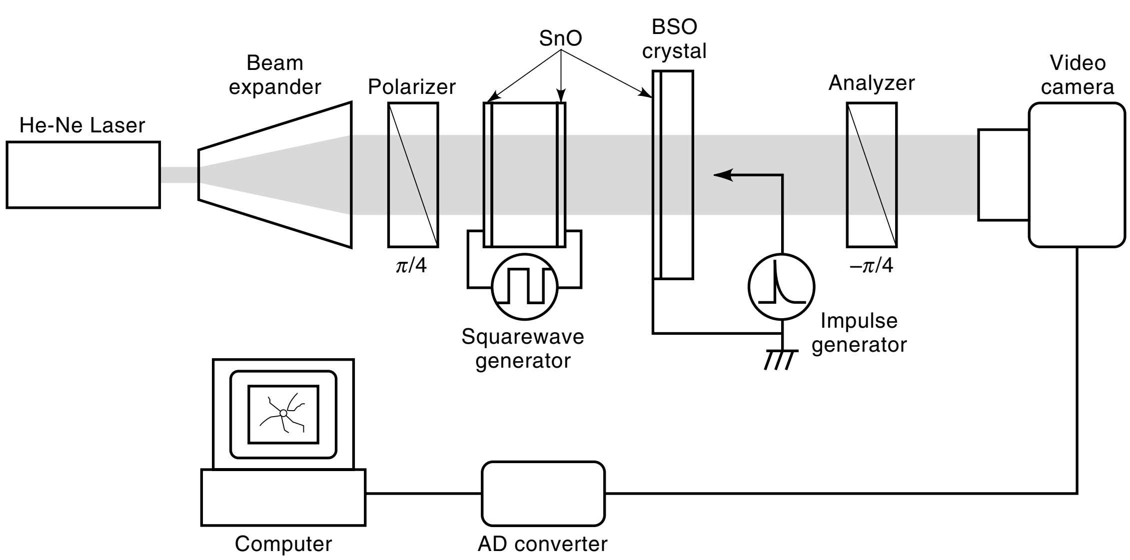
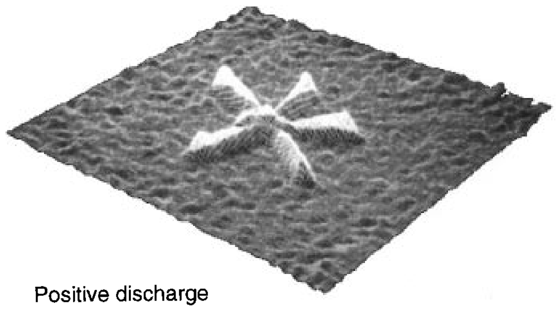


Figure 4. Two-dimensional lock-in amplifier system for surface-charge measurement.



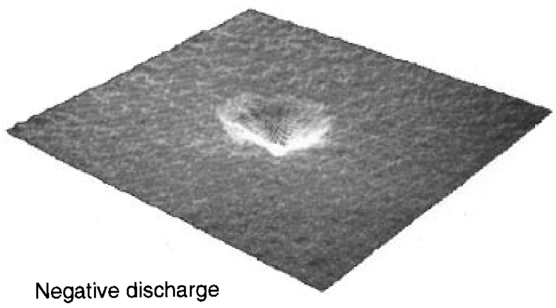


Figure 5. The surface-charge distribution on a BSO crystal. This figure shows that a treelike charge pattern remains on the surface after a positive discharge. With a negative discharge, on the other hand, the charge pattern becomes round.

lot of images results in a high signal-to-noise (S/N) measurement.

Figure 5 shows the surface-charge distribution on a BSO crystal. It displays the surface discharge obtained by applying an impulse voltage to a needle electrode on the surface of the crystal. This figure shows that a treelike charge pattern remains on the surface in the case of a positive discharge. In the case of a negative discharge, on the other hand, the charge pattern is round. In this way, the electro-optical measurement system with a two-dimensional lock-in amplifier directly observes the accumulation of charge changing with time.

SPACE-CHARGE MEASUREMENT

Pressure-Wave Propagation Method

In general, there are two ways to obtain a pressure wave: a piezoelectric device and a pulse laser. This section introduces the laser-induced, pressure-wave propagation method, which has better spatial resolution of the charge distribution and signal-to-noise ratio (2). A plate sample is placed between two electrodes, as shown in Fig. 6. When an extremely narrow-pulse laser (<1 ns) is used to irradiate the grounded electrode on the left, the electrode surface rapidly expands by being heated and then generates a pressure wave. The pressure wave passes through the left electrode and propagates in the sample at the velocity of sound v (typical polymers have sound velocities of 2000 to 3000 m/s). The pressure wave compresses a limited part of the sample. When this pressure wave passes through the position where an internal charge exists,

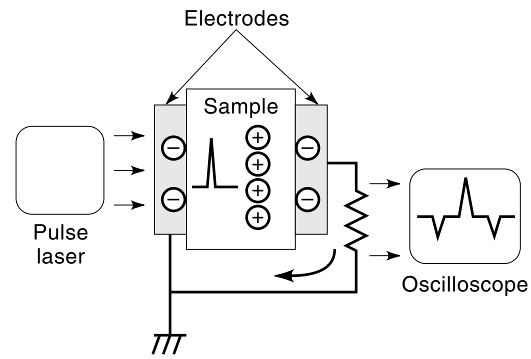


Figure 6. Laser-induced pressure-wave propagation method for space-charge measurement.

the charge is forced to move right and left, resulting in a current pulse flowing through the conductor connected to both electrodes. The magnitude and direction of the current pulse represent the charge quantity and polarity, respectively. The delay from the application of the pressure wave to the current pulse generation indicates the position of the internal charge. These relationships are shown in convolution as the following equation:

$$i(t) = A \int \rho(\tau) p(t-\tau)\, d\tau \tag{8}$$

where $p(t)$ is the pressure wave generated by the pulse laser, $\rho(t)$ is the space-charge distribution, and $i(t)$ is the current between both electrodes. Here, $p(t)$ is an extremely narrow independent pulse, so that the pulse is regarded as the delta function, and Eq. (8) is simplified as

$$i(t) = A' \rho(t) \tag{9}$$

where A and A' are sensitivity constants depending on the strength of the laser-induced pulse. Thus the waveform of the current shows the charge distribution directly. When the width of the laser-induced pulse is 100 ps, the spatial resolution of the internal space charge becomes less than 1 μm. The disadvantage of the pressure-wave propagation method is that the amplifier in the measurement system is destroyed when surface discharge on the sample or sample breakdown occurs during radiative exposure or high voltage applications.

Figure 7 shows the space-charge distribution in cross-linked polyethylene (XLPE) measured by the laser-induced, pressure-wave propagation method (3). Because XLPE has

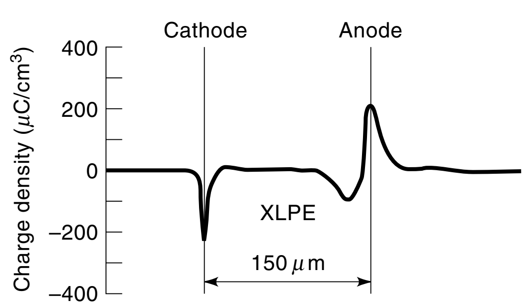


Figure 7. Space-charge distributions in an XLPE sheet measured by the laser-induced, pressure-wave propagation method.

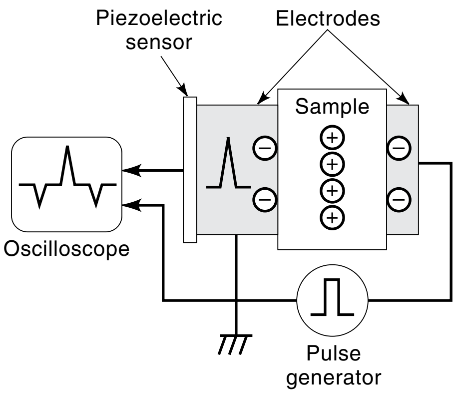


Figure 8. Pulsed electroacoustic (PEA) method for space-charge measurement.

higher thermal endurance than polyethylene, it is widely used for insulating power cables. The space charge was measured in the 150-μm XLPE film at 60°C under a 120 kV/mm dc electric field. Negative charge appeared near the anode just after the voltage was applied.

Pulsed Electroacoustic Method

The pulsed electroacoustic (PEA) method detects the space-charge distribution by a process opposite to that of the pressure-wave propagation method mentioned previously. A schematic diagram of the PEA method is shown in Fig. 8. When a narrow-pulse voltage is applied to the sample between the two electrodes, a pulse electric field is generated in the sample. This electric field $e_p(t)$ makes the space charge $\rho(x)$ generate a pressure wave because of its electrostatic force. The pressure wave propagates in the sample and the grounded electrode, and then the piezoelectric device under the grounded electrode changes it into an electric signal $v(t)$. The magnitude and direction of the pressure wave determine the quantity and the polarity of the charge. Because the delay appears when the pressure wave propagates from the position of the charge to the piezoelectric device, as in the pressure-wave propagation method, the space-charge distribution $\rho(x)$ can be observed by using the sound velocity of the sample as follows.

The pressure wave $p(t)$ generated in the sample due to the applied electric field is given by

$$p(t) = A \int \rho(\tau) e_p(t-\tau)\, d\tau \tag{10}$$

where $\rho(t)$ is the space-charge distribution, $e_p(t)$ is the pulse electric field applied to the sample, and A is a constant depending on the dielectric constant, the sound velocity, and the density of the sample. Then the output voltage of the piezoelectric device $v(t)$ is given by

$$v(t) = \int k(\tau) p(t-\tau)\, d\tau \tag{11}$$

where $k(t)$ is a specific function of the piezoelectric device and is a square function whose height and width depend on the sensitivity and thickness of the device. When the piezoelectric device is so thin that the width of $e_p(t)$ is narrow enough, both $e_p(t)$ and $k(t)$ are regarded as individual pulses similar to delta functions. In this case, $p(t)$ equals $A\rho(t)$, and Eq. (11) is simplified as

$$v(t) = A'\rho(t) \tag{12}$$

Thus, the waveform of the output signal indicates the space-charge distribution. Although this method has slightly poor spatial resolution, it has the advantage that the measurement system is never destroyed when a discharge occurs at any place because the detection circuit is electrically insulated from the other parts of the electrode system, such as the high-voltage bias circuit. In particular, a system with an optical fiber for the output signal cable can carry out the space-charge measurement even during a dc breakdown test at 500 kV.

Figure 9 shows the time dependence of the space-charge distribution of XLPE (100 μm) under 10 kV. A packet charge is injected from the anode just after the voltage application, and it moves toward the cathode. Because the charge injection decreased the interface electric field at the anode, the next injection did not occur.

Deconvolution Signal Processing

As shown in Eqs. (8) and (11), the space-charge measuring methods mentioned previously detect a signal that includes a lot of factors, such as the waveform of the laser pulse, the waveform of the applied pulsive voltage, the frequency characteristics of the piezoelectric device and amplifiers, and so on. These unknown factors should be compensated for to avoid errors with a deconvolution technique by using a reference signal (5). In general, when the measurement system keeps its linearity, the input and output signals have the following relationship of convolution,

$$Y(f) = H(f) * X(f) \tag{13}$$

where $Y(f)$ and $X(f)$ are the Fourier-transformed signals of $y(t)$ and $x(t)$. In the measurements described, $y(t)$ is the output voltage of the amplifier observed by the oscilloscope, and $x(t)$ is the space-charge distribution $\rho(x)$. The sign $*$ is the function to multiply those components whose frequencies are the same. $H(f)$ is the transfer function of the measurement system obtained by Fourier transformation from the impulse re-

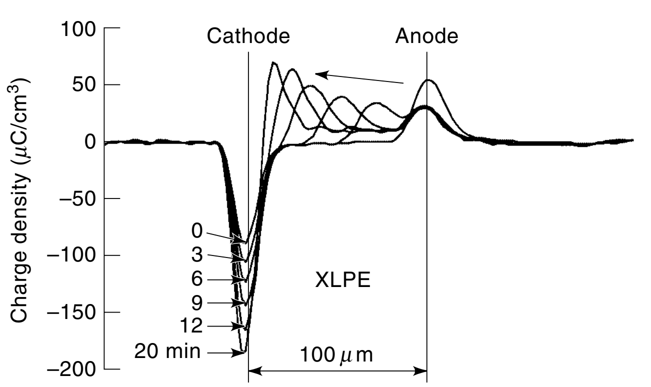


Figure 9. The time dependence of the space-charge distribution of an XLPE (0.1 mm) sheet under 10 kV. A packet charge is injected from the anode just after the voltage application, and it moves toward the cathode.

sponse of the system. Here the impulse response is obtained as follows.

When a dc voltage is applied to a sample without internal charge, such as a PET film, the charge distribution becomes the same as the sheet charge on both electrodes of a parallel plate capacitance. The signal due to the accumulated charge on the one side can be regarded as an impulse (delta function) with no width in the depth direction, resulting in the impulse response itself. Because the accumulated charge q_0 is calculated easily, the Fourier-transformed Q_0 becomes a constant, independent of the frequency. When the first peak included in the output signal is described as $v_0(t)$, the Fourier-transformed $V_0(f)$ becomes

$$V_0(f) = H(f) * Q_0 \tag{14}$$

$$V(f) = V_0(f)/Q_0 * R(f) \tag{15}$$

Then, in general,

$$R(f) = Q_0 V(f)/V_0(f) \tag{16}$$

This equation, a division at the frequency region that is deconvolution, represents the Fourier-transformed, space-charge distribution. Thus, the real charge distribution is calculated by inverse Fourier transformation of $R(f)$. In practical analysis, a low-pass filter is needed to reduce the noise and division by zero in the high frequency region.

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CHARGE MEASUREMENT. See ELECTROMETERS.

CHARGE STORAGE AND DIPOLE ORIENTATION. See ELECTRETS.