

# Non-contact surface resistivity measurement for materials greater than $10^9 \Omega$

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**Abstract.** A non-contact surface resistivity probe for materials with resistivity greater than  $10^9 \Omega$  has been developed using surface potential measurement combined with corona charging. The probe is composed of a grid type corona charger and a surface voltmeter located next to the charger. A test material was placed below the probe without contact to the material at a gap of 2 mm. The time variation of the surface potential and the saturation surface potential beneath the charged area are theoretically a function of the surface resistivity; therefore, measurement of the rise time and the saturation potential can be used to predict the surface resistivity in the ranges of lower and higher surface resistivity, respectively. The calibration equation for the probe was determined by solving the circuit equation for a one-dimensional simple circuit model and by extension of the simple model to the actual probe arrangement using experimentally derived constants. The lower surface resistivity,  $\rho_{sal}$  (from  $10^9$  to  $8 \times 10^{13} \Omega$ ), can be predicted from  $\rho_s = 1.0 \times 10^{11} \times T_m^{1.64}$  using a 63% rise time,  $T_m$ . The higher surface resistivity,  $\rho_{sah}$  (from  $8 \times 10^{13}$  to  $10^{16} \Omega$ ), can be predicted using the equation  $\rho_s = 3.0 \times 10^{14} \times V_m^{1.70}$  with the converted surface potential,  $V_m$ .

## 1. Introduction

Surface resistivity is one of the most important properties of materials when contact charging or triboelectric charging of the surface may cause electrostatic problems. In this case, an insulative surface should be coated with a conductive layer that has a surface resistivity ranging from  $10^6$  to  $10^{10} \Omega$  to gently eliminate the surface charge. There are surface resistivity probes with two of four electrodes that contact the test surface to apply voltage and measure the leakage current flowing through the surface. However, this measurement principle requires that an extremely small leakage current be measured for materials in the high surface resistivity range. In addition, the contact condition of the electrodes (difference of real contact area) on the surface may affect the measurement, thereby making it difficult to obtain an accurate measurement. The maximum of the measurement range for a typical surface resistivity probe is  $10^{13} \Omega$ . We have proposed a non-contact surface resistivity measurement technique that employs corona charging combined with surface potential measurement [1]. The maximum measurement range can be theoretically extended past  $10^{15} \Omega$ . This paper describes the calibration of the probe.

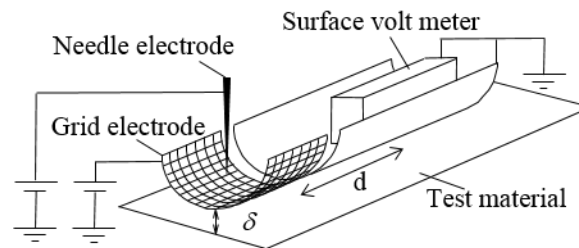
## 2. Theoretical

Figure 1 depicts the non-contact surface resistivity measurement system, which includes a probe and the test material. The probe is composed of a corona charger and a surface voltmeter. The corona charger has a needle and a grid electrode that provides surface charge to the test material placed below the probe with a gap of  $\delta$ . The charged potential is controlled by the voltage applied to the grid electrode,  $V_0$ .



However, the surface charge on the test material extends over the surface, depending on the surface resistivity; therefore, the change in the surface potential at the outside of the charged area is also dependent on the surface resistivity. The bottom shape of the grid electrode and the body of the potential probe are cylindrical to direct the surface charge from below the grid to below the surface voltmeter. The surface potential measured with the surface voltmeter eventually becomes  $V_0$  if the surface is conductive. The rise time of the surface potential is measured to estimate the surface resistivity as described below.

In a simple one-dimensional model [1], the equivalent circuit equation becomes equation (1) using the surface potential  $v(x,t)$  of the test sample:



**Figure 1.** Non-contact surface potential probe.

$$\frac{\partial^2 v(x,t)}{\partial x^2} - \frac{\rho_s}{\rho_v \delta} v(x,t) - \frac{\epsilon_0 \rho_s}{\delta} \frac{\partial v(x,t)}{\partial t} = 0, \quad (1)$$

where  $x$  is the distance from the charge area (below the grid) to the measured point (below the surface voltmeter),  $t$  is the elapsed time from charging,  $\rho_s$  is the surface resistivity of the test material,  $\rho_v$  is the volume resistivity of the air gap,  $\delta$  is the gap between the test material and the probe, and  $\epsilon_0$  is the permittivity of air. The time variation of the surface potential  $v(x,t)$  can be predicted by solving equation (1). The surface potential is a function of  $\rho_s$ ,  $x$ , and  $t$ ; therefore, the surface resistivity can be predicted by measuring the surface potential at a specific  $x$  and  $t$ . To obtain the simple solution of equation (1), two different conditions of lower or higher surface resistivity were considered as follows.

For low surface resistivity,  $\rho_s \ll \rho_v \delta$ , so that the second term of equation (1) can be omitted and  $v(x,t)$  becomes equation (2) under the boundary condition  $v(0, t) = V_0$ :

$$v(x,t) = V_0 \operatorname{erfc} \left\{ \left( \frac{\epsilon_0 \rho_s}{4t\delta} \right)^{\frac{1}{2}} \cdot x \right\}, \quad (2)$$

where  $\operatorname{erfc}$  is the complementary error function. At fixed  $x=d$ , the normalized surface potential  $v(d,t)/V_0$  changes from 0 to 1. For measurement of the surface potential, the 63% rise time,  $T_m$ , can be measured when the normalized surface potential  $v(d, T_m)/V_0$  becomes 0.63. The theoretical lower surface resistivity  $\rho_{stl}$  becomes

$$\rho_{stl} = \frac{4\delta}{\epsilon_0 d^2} \{ \operatorname{erfc}^{-1}(0.63) \}^2 \cdot T_m = A_l \cdot T_m, \quad (3)$$

where  $A_l$  is a constant that depends on the dimensions of the probe and the probe set-up. Equation (3) shows that the surface resistivity can be predicted by measuring the rise time,  $T_m$ . Equation (3) shows the theoretical surface resistivity derived from the simple one-dimensional model; therefore, the actual surface resistivity of a three-dimensional set-up may be different. We can suppose the constants  $D$  and  $\beta_l$  to transform from the one-dimensional theoretical surface resistivity,  $\rho_{stl}$ , to the actual surface resistivity,  $\rho_{sal}$ , to be as shown in equation (4), considering the large dynamic range.

$$\log_{10} \rho_{sal} = D + \beta_l \cdot \log_{10} \rho_{stl}. \quad (4)$$

Hence, the actual surface resistivity  $\rho_{sal}$  can be obtained from equation (5):

$$\rho_{sal} = 10^D \cdot (A_l \cdot T_m)^{\beta_l} = \alpha_l \cdot T_m^{\beta_l}, \quad (5)$$

where both  $\alpha_l$  and  $\beta_l$  are constant values determined by calibration experiments using known surface resistivities of test materials.

For the higher surface resistivity range, the surface charge moves extremely slowly and the surface potential  $v_{sat}$  becomes smaller than  $V_0$ . In this case, the third term of equation (1) can be omitted, so that  $v_{sat}$  under the boundary condition  $v=V_0$  at  $x=0$  becomes

$$v_{sat} = V_0 \exp \left\{ - \left( \frac{\rho_s}{\rho_v \delta} \right)^{\frac{1}{2}} \cdot x \right\}. \quad (6)$$

The theoretical surface resistivity for the higher range  $\rho_{sth}$  becomes equation (7) using the surface potential at  $x = d$ :

$$\rho_{sth} = \frac{\rho_v \delta}{d^2} \left\{ \log_e \left( \frac{V_0}{v_{sat}(d)} \right) \right\}^2 = A_h \cdot V_m^2, \quad (7)$$

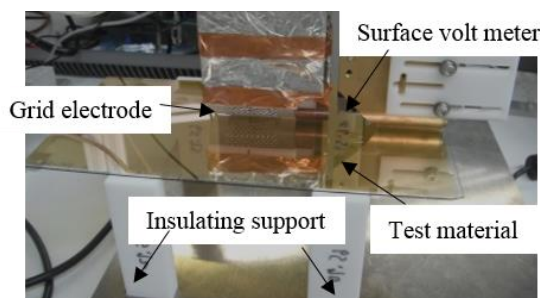
where  $A_h$  is a constant that depends on the dimensions of the probe and the probe set-up.  $V_m$  is the converted surface potential by taking the natural logarithm of  $V_0/v_{sat}(d)$ . By considering the relationship between the theoretical and actual surface resistivity, as in equation (4), the actual surface resistivity can be expressed in the form

$$\rho_{sah} = \alpha_h \cdot V_m^{\beta_h}, \quad (8)$$

where both  $\alpha_h$  and  $\beta_h$  are constants determined by calibration.

### 3. Experiment and results

Figure 2 shows a photograph of the experimental setup, which includes the non-contact surface resistivity probe and a test material. The size of the grid electrode is  $0.9 \times 0.9 \text{ mm}^2$ , and the radius of the cylindrical mesh and grounded body is 10 mm. The distance  $d$  between the charged and measurement spots is 50 mm. The gap  $\delta$ , between the probe and the test material is 2 mm. The voltage applied to the grid electrode  $V_0$  was 500 V, while +3.5 kV dc is applied to the needle electrode to start the corona discharge. Table 1 shows test materials prepared on glass substrates. Samples A and B are n-type impurity-doped amorphous silicon. Samples C and D are polysilicon from amorphous silicon by annealing with a laser. Sample E is indium gallium zinc oxide (IGZO). Each of the materials is commercially used as a core material in liquid crystal displays (LCDs). The time variation of the surface potential  $v(t)$  was measured and recorded with a personal computer (PC) through an



**Figure 2.** Experimental setup.

**Table 1.** Prepared test materials

Sample	Surface resistivity ( $\Omega$ )	Material
A	$6.67 \times 10^7$	n+a Si
B	$5.56 \times 10^8$	n+a Si
C	$1.65 \times 10^{11}$	Poly Si
D	$7.37 \times 10^{11}$	Poly Si
E	$6.90 \times 10^{14}$	IGZO

analog-digital (A-D) converter. The normalized surface potential  $v(t)/V_0$  was calculated and the 63% rise time was measured.

Figure 3 shows the time variation of the normalized surface potential  $v(t)/V_0$  for each sample. The surface potential increased with time and eventually reached 1. A higher surface resistivity results in a larger rise time. Figure 4 shows the relationship between the surface resistivity and the 63% rise time,  $T_m$ . As predicted in equation (5), there is a linear relationship between the rise time and the surface resistivity. From the experimental data, the two constants  $\alpha_l$  and  $\beta_l$  in equation (5) were obtained as  $\alpha_l = 1.0 \times 10^{11}$  and  $\beta_l = 1.64$ .

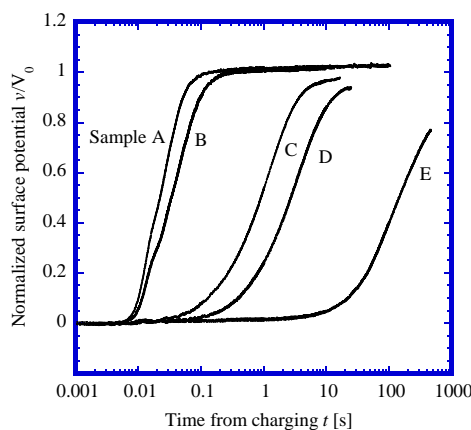
In the rise time measurement, the measurement time for higher surface resistivity became extremely long. For example, the rise time from measurement of a sample with a surface resistivity over  $8 \times 10^{13} \Omega$  became larger than 60 s. Equation (6) indicates the saturation surface potential for a higher surface resistivity sample; therefore, the surface potential calculated from equation (2) should be less than that calculated from equation (6). The calculated potential from equation (6) is theoretically close to the potential of equation (2) at  $t = 60$  s. Hence, equation (8) should be effective when the 63% rise time is greater than 60 s. From the experimental data, the two constants  $\alpha_h$  and  $\beta_h$  in equation (8) were obtained as  $\alpha_h = 3.0 \times 10^{14}$  and  $\beta_h = 1.70$ .

The minimum measurement limit of the probe is dependent on the response time of the surface voltmeter. The response time of the probe is 20 ms; therefore, the minimum measurement limit of the surface resistivity is approximately  $1 \times 10^9 \Omega$ . Thus, a much faster response time of the surface voltmeter is required for the measurement of lower surface resistivity. On the other hand, the maximum limit of the measurement is dependent on the voltage resolution of the potential probe. The voltage resolution of the potential probe is a few tens of millivolts; therefore, the maximum detection limit of the surface resistivity is approximately  $1 \times 10^{16} \Omega$ . It is important that such a high surface resistivity can be measured without contact to the test material. However, in the high surface resistivity region greater than  $10^{14} \Omega$ , precise measurement of the surface resistivity of test samples using a contact type probe, such as two-terminal or four-terminal measurement, is difficult because the leakage current is significantly small. Hence, calibration of the higher surface resistivity range may include uncertainty, so that a standard test sample is necessary for more precise calibration.

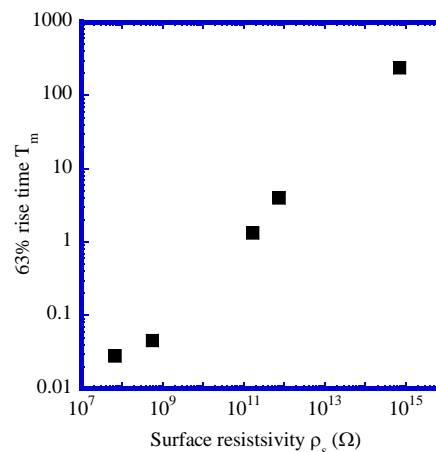
#### 4. Conclusion

A non-contact surface resistivity probe was designed using corona charging combined with surface potential measurement and calibrated. The possible measurement range was determined to be from  $10^9$  to  $10^{16} \Omega$ . Future work will include practical application of the probe for manufacturing qualification in industrial quality control and extension of the measurement range to lower than  $10^9 \Omega$ .

- [1] Sugimoto T Abe M and Higashiyama Y 2012 *Trans. IEEE Ind. Appl.*, **48** 1657-61



**Figure 3.** Time variation of  $v/V_0$ .



**Figure 4.** Relationship between  $\rho_s$  and  $T_m$ .