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The influence of electrode size on resistance measurement in the modified four-electrodes method

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ABSTRACT

The determination of resistivity of thin antistatic coatings with use of a modified four-points method is considered. 2D and 3D mathematical models taking into account cylindrical current electrodes and pin like voltage electrodes were developed. We analyzed how the size of current electrodes can change the determined resistivity. The effect of coating thickness and resistivity of the coating and background was tested. The theoretical considerations showed that the size of current electrodes has a relatively small influence on the detected resistivity. This observation was confirmed by experiments.

1. Introduction

Electrostatic discharges (ESD) due to natural and industrial processes create various problems and hazards. One of the most dangerous is fire or even explosion, which can occur when an ESD of high enough energy takes place in flammable gas or dust. Another threat is connected with personnel safety, as highly energetic ESD can be dangerous for human life. In addition, the electrostatic field generated by charged objects can cause disturbances in functioning of electronic equipment [1–3]. In most cases, these effects can be avoided by using proper – and thereby – effective ESD protection [4,5]. One of the methods used in such protection is coating objects with protective layer in the form of various varnishes and paints. The coatings also protect the objects against corrosion and other environmental impacts. In accordance with standards, anti-electrostatic coatings should have the volume resistivity not greater than $10^5\,\Omega$ m, and the surface resistivity not greater than $10^{10}\,\Omega$ [6]. However, these values strongly depend on the method used. In the case of the original four-points method, the detailed recommendations, methodology, information on accuracy, and used equipment can be found in [7,8]. It is required that the measurements have to be carried out in laboratory conditions on a suitably prepared sample. In practice, this is a serious limitation, because it makes it impossible to perform the measurements in-situ on a real object [4].

In this paper, we consider a modified four-points method. In particular, the considered model concerns the resistivity of anti-electrostatic coatings. The core of the paper is a theoretical model taking into account the dimensions of the sample, measurement system as well as the thickness and resistivity of the coating and background layer [4,9]. In the paper, we focused on the relation between the measurement electrodes size and other parameters, including the dimensions of the electrode system, the size of the measurement area, thickness of the coating, with background layer and resistivity ratio taken into account. This is to assess the maximum size of the measurement electrodes at which they can be regarded as practically negligible in size (point-like). The knowledge on these parameters allows us (within certain limits) ignoring the influence of the size and shape of the surface being tested, and sometimes also the type of substrate to which the coating was applied. The determined parameter limits are then verified on a real object.

The method is a modification of the classical four-points method and the method of Van der Pauw (VdP). The VdP method uses four electrodes, and is one of the most frequently used techniques of resistivity measurement of planar and thin samples of irregular shape. According to the method, the sample should be homogeneous and isotropic, of constant thickness and without holes (i.e. simply connected). The four pin electrodes are placed on the edge of the sample throughout its whole thickness [10–13]. The VdP method is commonly used in electric measurements and has many applications in physics, e.g. [14–16].

In this paper, we assume the four-points model and use the method of variable separation (amongst others) to obtain the

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theoretical relationships between material-geometrical parameters and the measured resistance under certain assumptions. Other aspects and details on the modification of four-points method, inter alia, the required spacing between the measurement electrodes for planar infinite sample and the size of the measurement area for planar finite sample have been determined and presented in [9,17].

2. Model studies

2.1. General assumptions for the modified four-electrodes system

The system consists of four electrodes making a square of side length b as in Fig. 1. Two of the electrodes, A and B, deliver current I_{AB} (briefly I) into the system of coating (top layer) and bulk (background layer), whereas the other two electrodes, C and D, detect the voltage U_{CD}. Then we define the following quantity:

$$R_{AB,CD} = \frac{U_{CD}}{I_{AB}}. \tag{1}$$

Under certain assumptions this relationship may be useful to determine the volume and surface resistivity. The surface resistivity determined in such a way will be an equivalent quantity, which effectively describes the bulk and coating together.

In the first approximation, considered in [9], it was assumed that the flat coating extends to infinity and the electrodes are pins touching the coating at points A, B, C and D. In the subsequent analysis, presented in [17], the finite dimensions of the coating were taken into account, yet the electrodes were still treated as infinitely thin. In this paper, we consider the influence of finite size of the current electrodes. Several simplifying assumptions were made as follows:

(a) The background layer (substrate) of constant thickness H is covered with coating of constant thickness h.
(b) The coating and the substrate have resistivity ρ_1 and ρ_2, respectively.
(c) The sample is a square of side length $2c$.
(d) The centers of the electrodes form a square of side length b.
(e) The current electrodes (A and B) are cylinders of radius $a > 0$.
(f) The voltage electrodes (C and D) are infinitely thin pins.

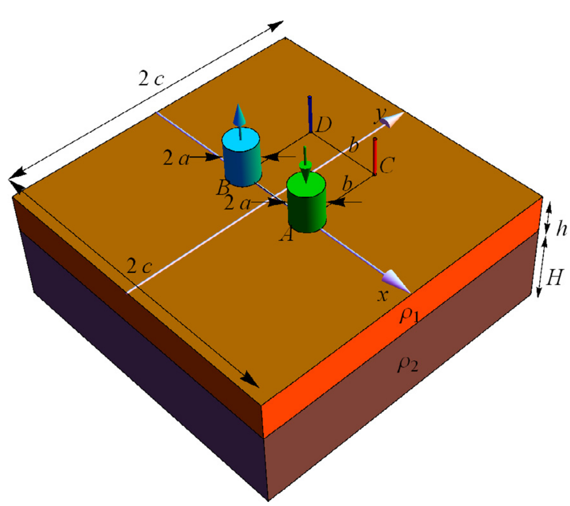

Fig. 1. Geometry of the modified four-points method: two cylindrical current electrodes (A and B) of radius a and two pin voltage electrodes (C and D) make a square of side length b and touch the coating of thickness h and resistivity ρ_1; the coating covers the background layer of thickness H and resistivity ρ_2; the sample is a square of side length 2c.

(g) The voltage electrodes do not affect the potential distribution inside the sample.
(h) The contacts electrode-coating and coating-substrate are perfect.
(i) The sample is placed in a non-conductive region (usually air).

Let us denote the potential distributions inside the coating and the background by V_1 and V_2, respectively. In theoretical considerations, the Cartesian coordinates will be used with $z = 0$ at the coating surface, $z = -h$ at the coating-background and x and y axes as in Fig. 1. According to assumption (i), the current does not flow across surfaces $z = 0$ (except for the contact with current electrodes) and $z = -h - H$. It does not flow across surfaces $x = \pm c$ and $y = \pm c$, either. The conditions for the coating-background contact ($z = -h$), according to assumption (h), have the form of general interface conditions for electroconductive field:

$$V_1|_{z=-h} = V_2|_{z=-h}, \quad \frac{1}{\rho_1}\frac{\partial V_1}{\partial z}\bigg|_{z=-h} = \frac{1}{\rho_2}\frac{\partial V_2}{\partial z}\bigg|_{z=-h}. \tag{2}$$

They can be simplified considerably in two cases:

I. the coating is much more conductive than the background layer ($\rho_1/\rho_2 \ll 1$),
II. the coating is much less conductive than the background layer ($\rho_{1/}\rho_2 \gg 1$).

These two cases can be modeled as $\rho_1/\rho_2 \to 0$ and $\rho_{1/}\rho_2 \to \infty$, respectively. They are treated as special cases of the general solution. One exception is a 2D model for $\rho_1/\rho_2 \to 0$, which is considered first.

2.2. Infinite planar system with highly conductive coating

If the bulk is much less conductive than the coating, the second of Eqs. (2) yields

$$\frac{\partial V_1}{\partial z}\bigg|_{z=-h} = \frac{\rho_1}{\rho_2}\frac{\partial V_2}{\partial z}\bigg|_{z=-h} \approx 0. \tag{3}$$

Therefore, we can consider only the coating in such a case. The simplest model taking into account the finite size electrodes originates from the one which was described in [9] with Eqs. (3), (4). The model considered there treats the current electrodes as filaments injecting currents I and $-I$ at points ($b'/2$, 0) and ($-b'/2$, 0), respectively (in the original paper symbol b was used instead of b', but here b is reserved for the distance between the centers of the cylindrical electrodes). The elementary field theory handbooks often

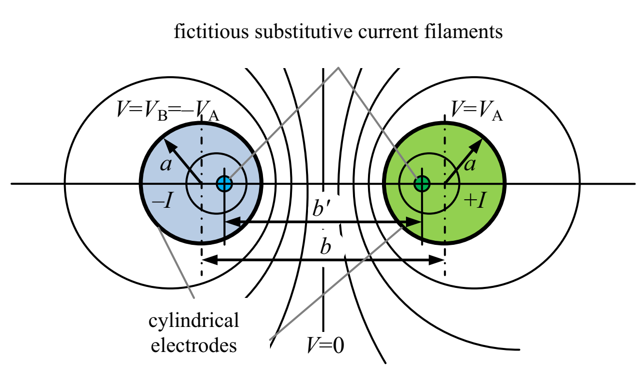

Fig. 2. The electrical potential around two parallel cylinders of radius a and centers displaced by a distance of b is the same as generated by two parallel filaments displaced by a distance of b'.