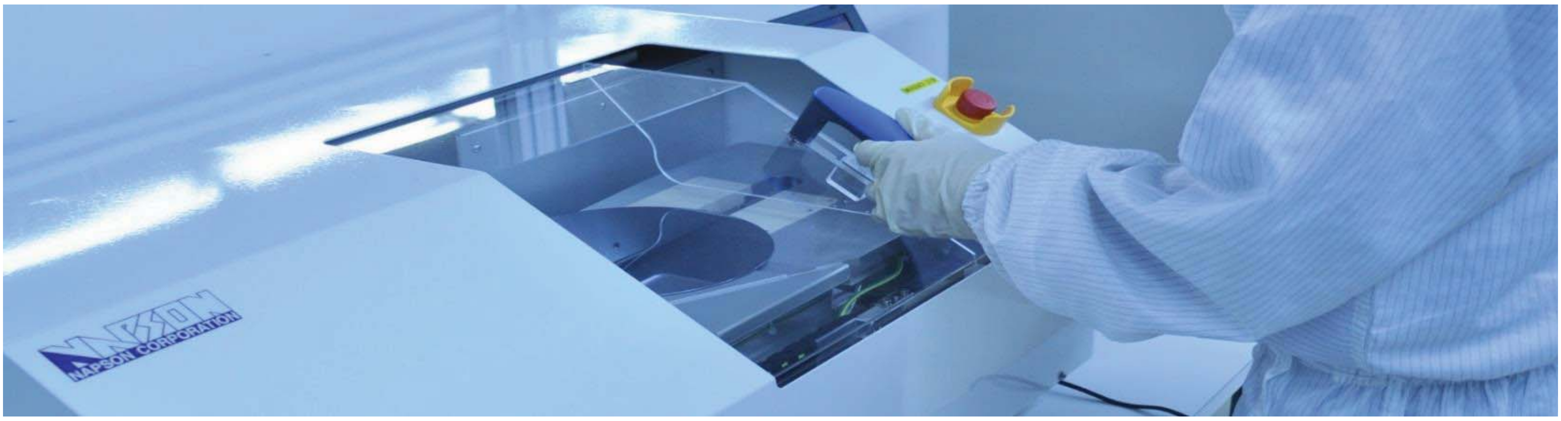
Measurement principles & methods of Resistance

(Resistivity, Sheet resistance)



NAPSON CORPORATION

The Pioneer
for Sheet resistance/Resistivity
measurement

Ver. 2.0
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1. Objective of resistance measurement

In general, as the evaluation of the conductive for material, the electrical resistance (Resistance) has been used.

There are 2 objectives of evaluating and measuring the electrical resistance.

1) Research and development of materials
-Characterization of newly developed substances.
-The characteristic change due to the change in the sample shape and use environment.
Electrical resistance is one of the most important evaluation item for such kind of situation as above.

2)Quality assessment and management of product
If there is a defect or defective product, the impact will appear in electric resistance.
Therefore, as one of the guidelines for quality assessment and management, electrical resistance values are used.
It is also used to inspection check of goods purchased as a material of processed products.
(eg. Si wafer and cell electrode)

Not only as a direct evaluation method as resistance measurements, it also used as an indirect method of evaluating to some relevant items.
(such as the detection of thin film defect sites such as above item 2)

Electrical resistance ＝ Ω [ohm]

⇒ Unit representing the flow difficulty of the current

$$R = V / I$$ **V＝voltage、I＝current*

Unit of electrical resistance, are also used selectively by the shape of the material.
Depending on the measurement material and/or industry segments, it has the case that differs unit of the electrical resistance that is used.
(Because There is the unit of electric resistance defined by industry standards for each industry, like JIS)

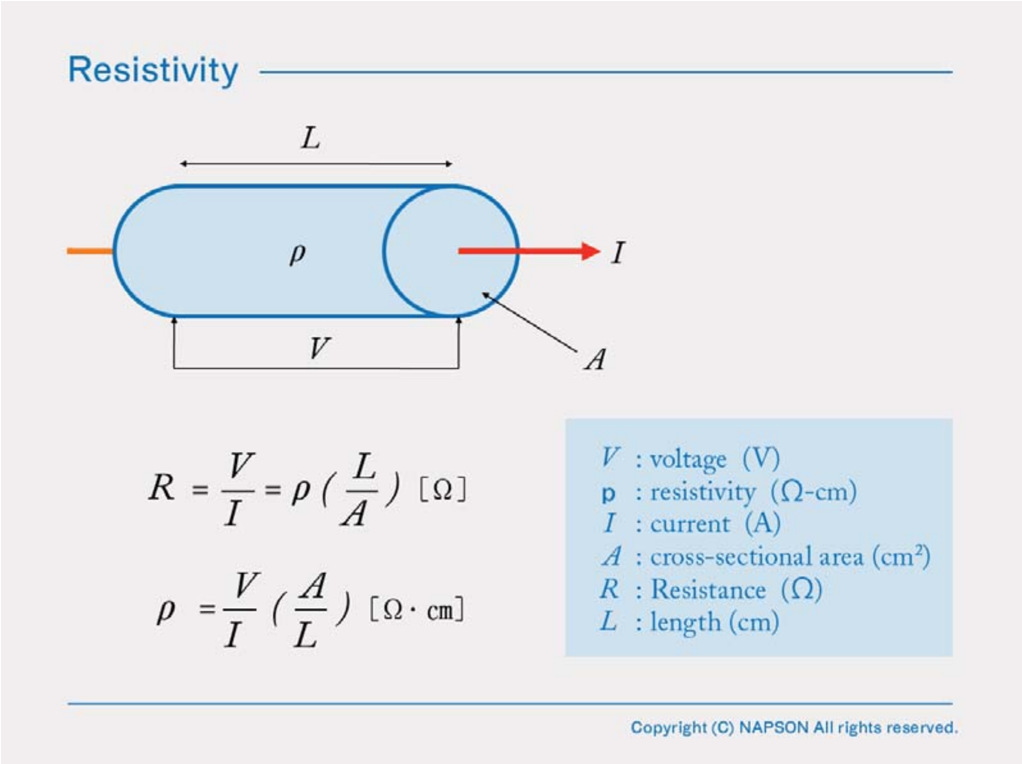
In Napson's resistance measurement system, in addition **to resistance [Ω],** also correspond to the unit display in **resistivity [Ωcm]** and **sheet resistance [Ω / □]**.

We will continue to describe specific measuring method of calculation on the following page.

2. Measurement unit ; Resistivity

Resistivity = Ωcm [ohm centimeter]

⇒ Volume resistance of material



*Resistivity is expressed as specific electrical resistance.

Resistivity is used to represent the electrical resistance of thick materials.
(Silicon wafer and/or bulk, conductive rubber & plastic etc)

Electrical resistance: When the electric resistivity is ρ, the length is L and cross-sectional area for a conductor is A

The R is givin by ;

$$R = \rho \times [L/A]$$

Where ρ is given by ;

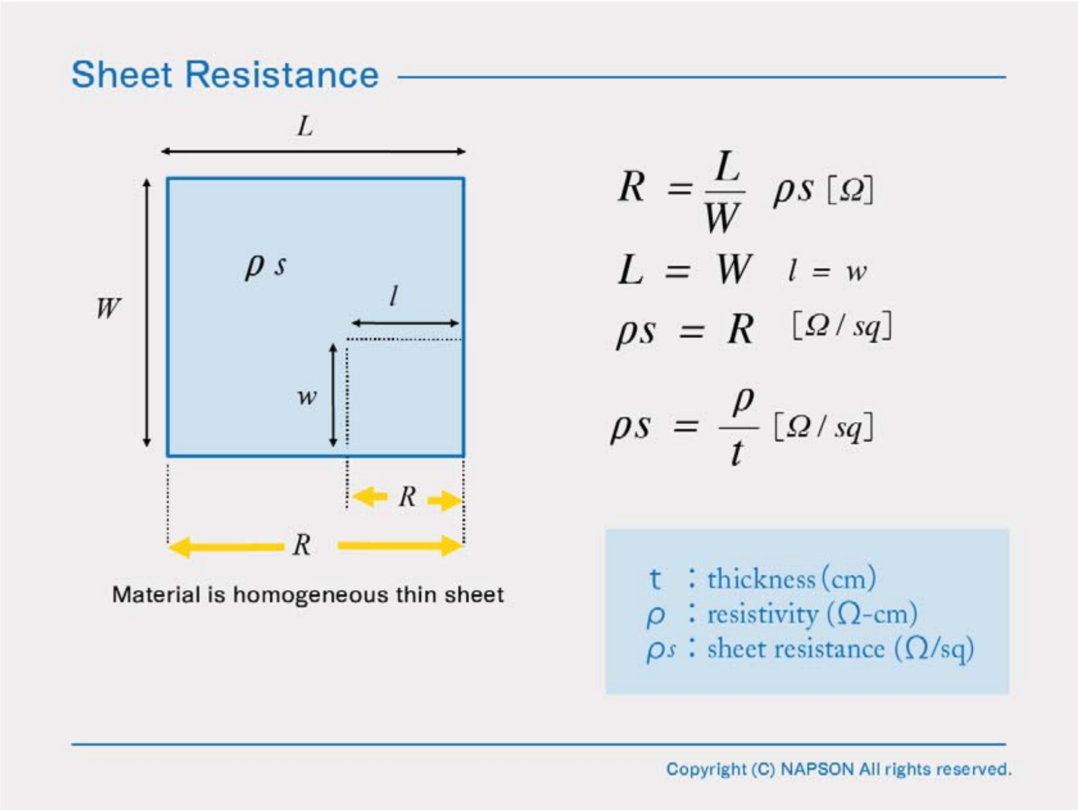
$$\rho = V/I \times [A/L]$$

*When the unit is set to Ω-cm, the volume is shown by cubic measure, such as 1cm x 1cm x 1cm.
It may be shown by Ω-m (ohm meter) depending on the measuring object.

3. Measurement unit ; Sheet Resistance

Sheet resistance = Ω/□ [Ohm per Square]

⇒ Surface resistance of marterial



Sheet resistance is used to represent the electrical resistance of the sheet-like sample.
(Layer sample, Thin film and/or Thin film layer on base material)

When it expresses three-dimensional conductivity, resistance is givin by

$$R = \rho \times L/A = L/zW \times \rho s$$

When the length of a sample[L] and the width[W]are equal, the resistance[R] and he sheet resistance[ρ] will become equal.

“Moreover, Sheet resistance[ρs] is the value which divided resistivity[ρ] by thickness[t] .”

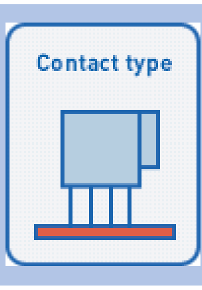
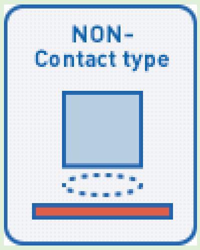
4. 2 kinds of Measurement methods (Contact & Non-contact)

Napson is the only vendor in the world, who manufactures and sells 2 kinds of resistance measurement methods(Contact & Non-contact).

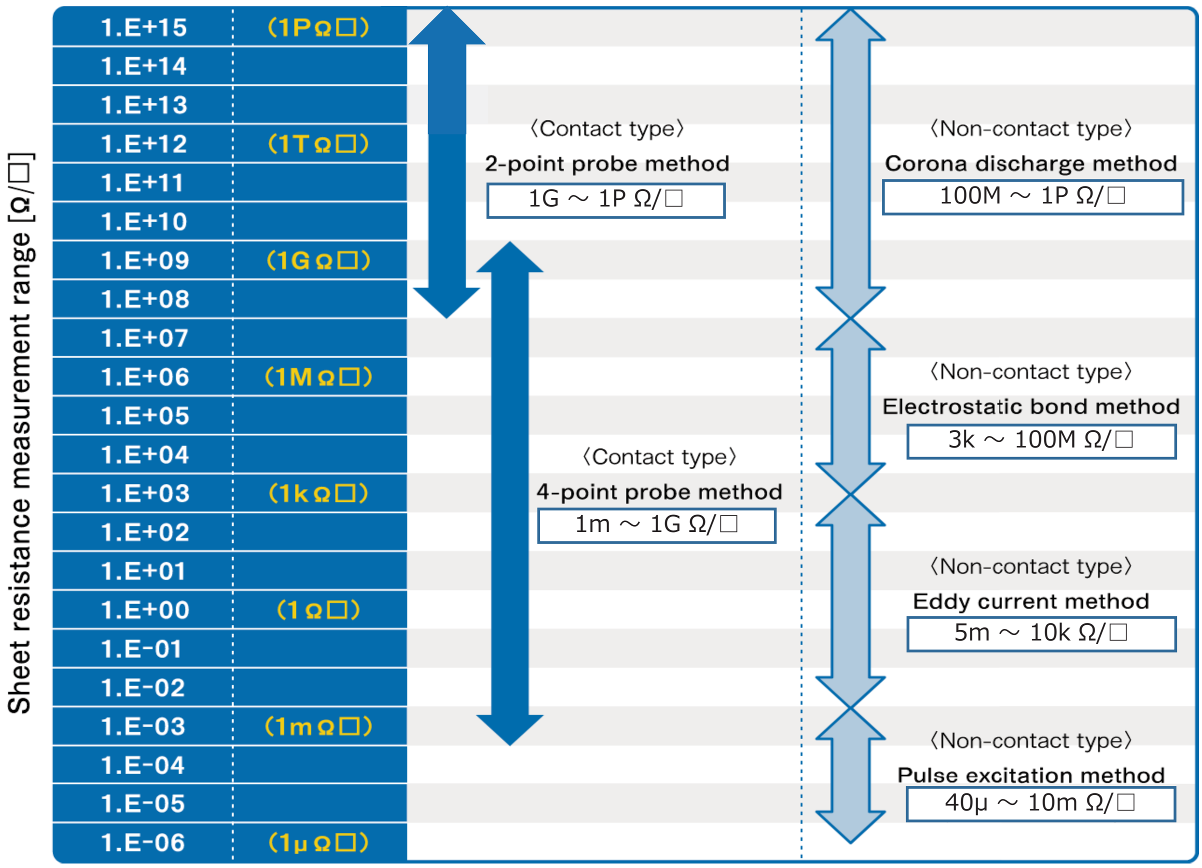
Contact types with 4-point probe and Non-contact types, such as eddy current measurement.

Here are the electrical resistance principles which can be measured by Napson resistance measurement systems.

Users can consider which system to install by the features of the each measurement principles and corresponding range.

Measurement Method		
Advantage	**・Measurement is absolute** **・Narrow measurement area**	**・No damage & influence** **・No influence of contact resistance**
Disadvantage	**・Sample may be damaged by probe contact**	**・Calibration to a reference resistivity sample is required** **・Sample thickness is limited by probe gap**

<Measurement range chart for each measurement method>



5. <Contact type> 4-point probe

This paragraph describes the resistance measurement principle for a contact type (4-point probe measurement method)

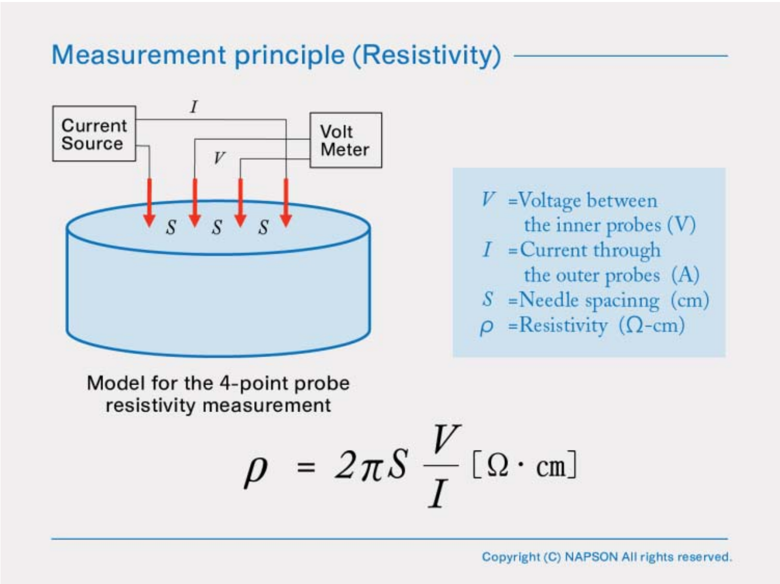
4-point probe method can measure 1E-3 (1m) ~ 1E + 9 (1G) Ω / □ level of resistance range.

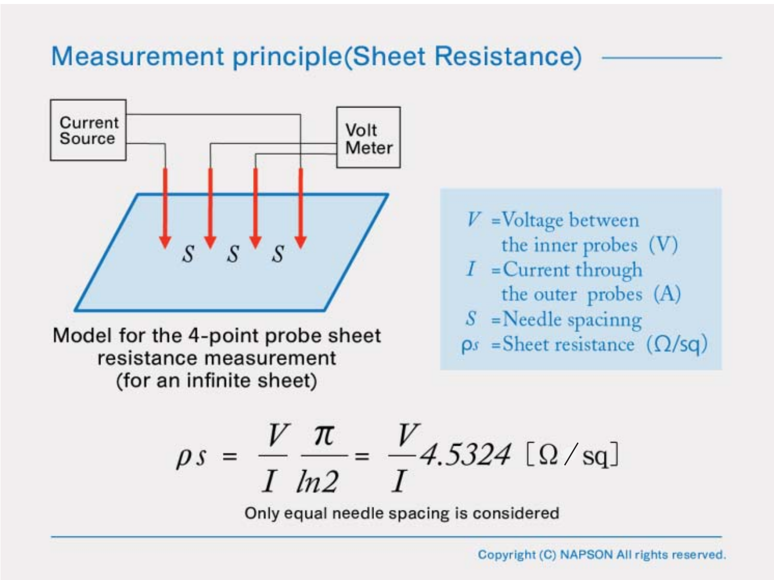
It is a basic measurement technique to the electrical resistance measurement in a wide range of industries.

4-point probe method measured by the following procedure;

1) Put on a straight line the four needle-shaped electrode in the measurement sample surface.
2) Apply the constant current to the outer two probes.
3) By measuring the potential difference between the inner two probes to obtain the resistance.

As shown in the figure below, Resistivity measurement & sheet resistance measurement are the same measurement principle.





4-point probe measurement systems made by Napson serve as a measuring method and the compensation method based on JIS and an ASTM(SEMI) standards.

This system is relied upon as an industrial standard measurement system by the silicon wafers/ingots related users in Japan and Asia.

Moreover, it provides traceability to NIST (National Institute Standard Technologies[USA]) standards and resistivity samples.

Instruments/ systems are shipped after calibrations and careful testing with standard samples at the factory.

The Napson 4-point probe method instrument complies with the following Japanese Industrial Standards (JIS)and American Society for Testing and Materials (ASTM).

<Japan Industrial Standards>

JIS H 0602-1995

Testing Method Of Resistivity For Silicon Crystals And Silicon Wafers With Four-point Probe

JIS K 7194-1994

Testing method for resistivity of conductive plastics with a four-point probe array

<American Society for Testing and Materials>

ASTM F 84-99 （SEMI MF84）

Standard Test Method for Measuring Resistivity of Silicon Wafers With an In-line Four-Point Probe

ASTM F 374-00a

Standard Test Method for Sheet Resistance of Silicon Epitaxial, Diffused, Polysilicon and Ion-implantedLayers Using an In-Line Four-Point Probe with the Single-Configuration Procedure

ASTM F 390-11

Standard Test Method for Sheet Resistance of Thin Metallic Films With an Collinear Four-Probe Array

ASTM F 1529-97

Standard Test Method for Sheet Resistance Uniformity Evaluation by In-Line Four-Point Probe with the Dual-Configuration Procedure

6. <Contact type> 2-point probe

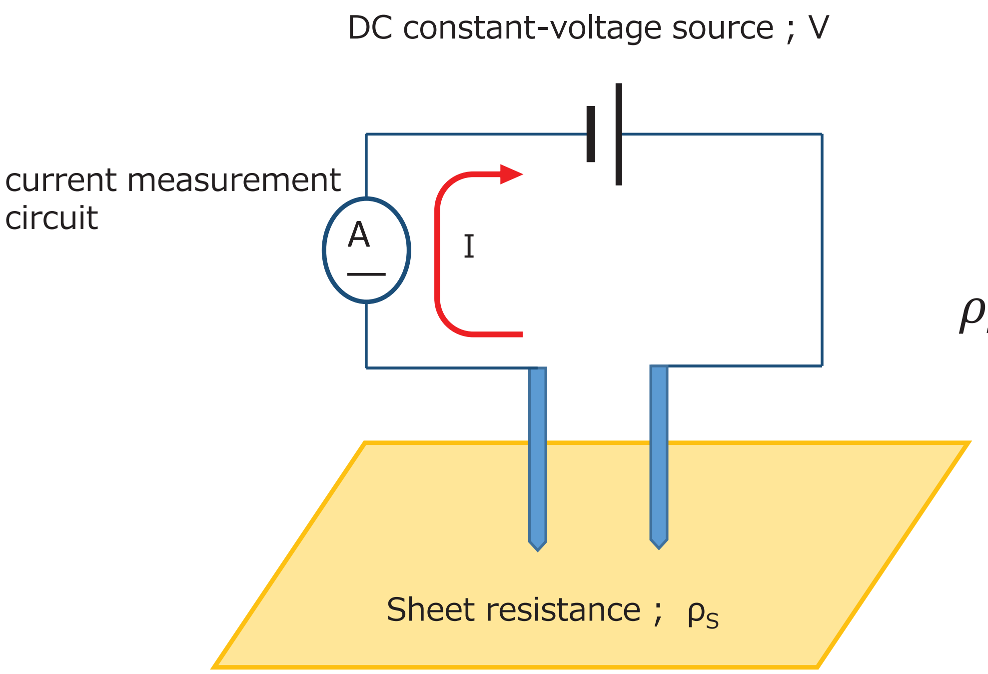
This paragraph describes the high-range resistance measurement principle for a contact type (2-point probe measurement method)

2-point probe method can measure 1E-9 (1G) ~ 1E + 15 (1P) Ω / □ level of resistance range.
It is used to measure the sample such as insulation materials like conductive rubber.

As shown in FIG. 1, 2-point probe method measuring system consists of DC constant voltage source, current measuring circuit and dedicated probe.
The measurement circuit formed by measurement system and the sample are connecting in series.

When a voltage(V) is applied, almost all of the number of test voltage will appear at both ends of the sample resistance.
(Because of the sample resistance is greater than the internal resistance of the current measurement circuit)

Therefore, it applies Ohm's law to the value of the current (I), can be calculated V / I ratio[Ω] of the sample.
In addition, multiplying the KP coefficients(determined by the geometry of the probe in contact with the sample) to this value, can calculate the surface resistance ρS [Ω / □].



$$\rho_S = K_P \times \frac{V}{I} \quad [\Omega/\square]$$

Fig.1 High-resistance measurement circuit by constant-voltage process

The current becomes very small when resistance of the sample is increased when measured by 2-point probe method. In that case, it may need to increase the applied voltage.

In general, High resistance often to have a voltage coefficient, so the measured value sometimes changed by the value of applied voltage. It also depends on the length of the energization time.

The surface resistance of the high resistance material is easily affected by environmental changes(especially by humidity).
For this reason, it is important to manage and use the measurement system and sample under certain circumstances.
In addition, the measured value is also affected by factors such as pollution and electrostatic charging of sample surface.

The coefficient[KP] for calculating formula which came out on the previous page has been determined for ach of the two types of probe shape as followings.

<2-point probe>

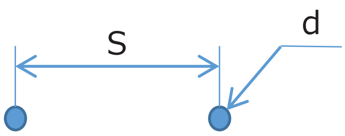


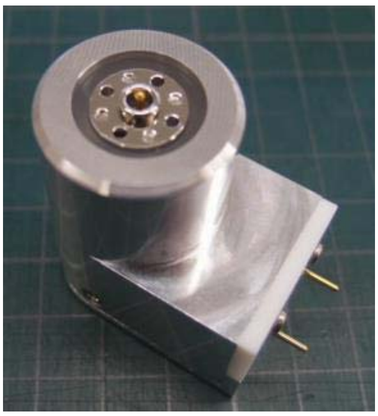
Fig.2
contact domain by 2-point probe

S = Needle spacing (typical value : 4mm)

d = Needle diameter for contact surface
(expected value : 5~50μm)

$$K_P = \frac{\pi}{\cosh^{-1}\left(\frac{S}{d}\right)} \cong 0.4\sim0.6$$

< Reduced diameter ring probe>



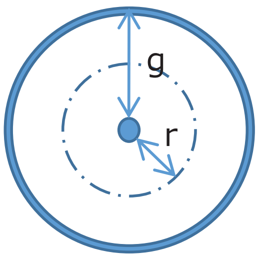


Fig.3
Contact surface by reduced diameter ring probe

$$K_P = \frac{2\pi r}{g} = \frac{2\pi r}{2r} = \pi$$

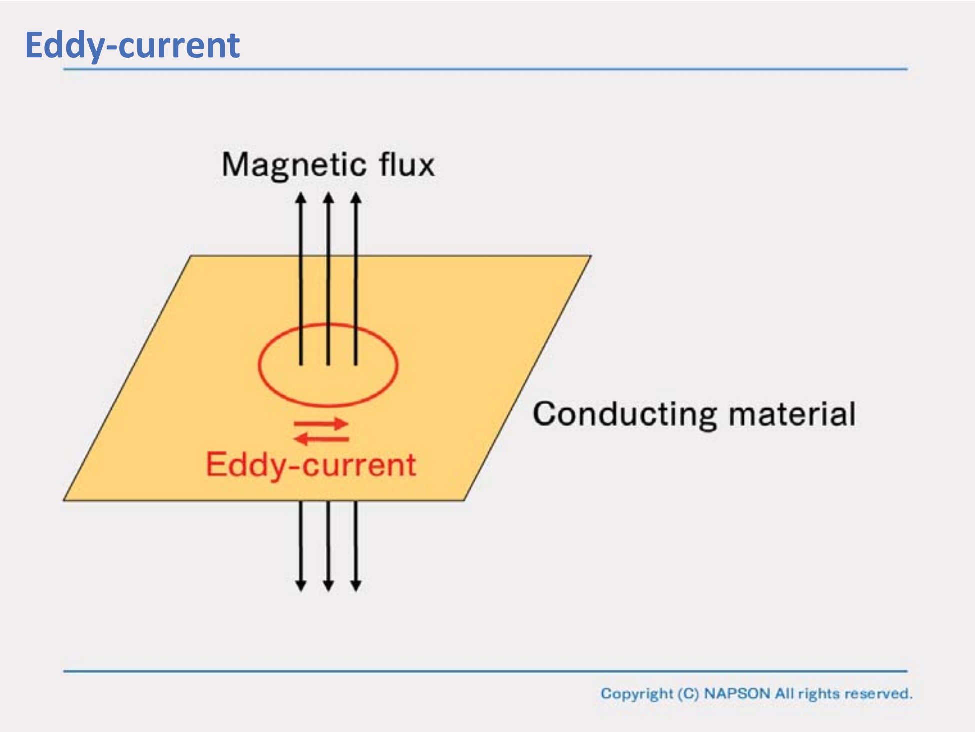
7. <Non-contact type> Eddy-current

This paragraph describes the non-contact resistance measurement principle by eddy-current method.

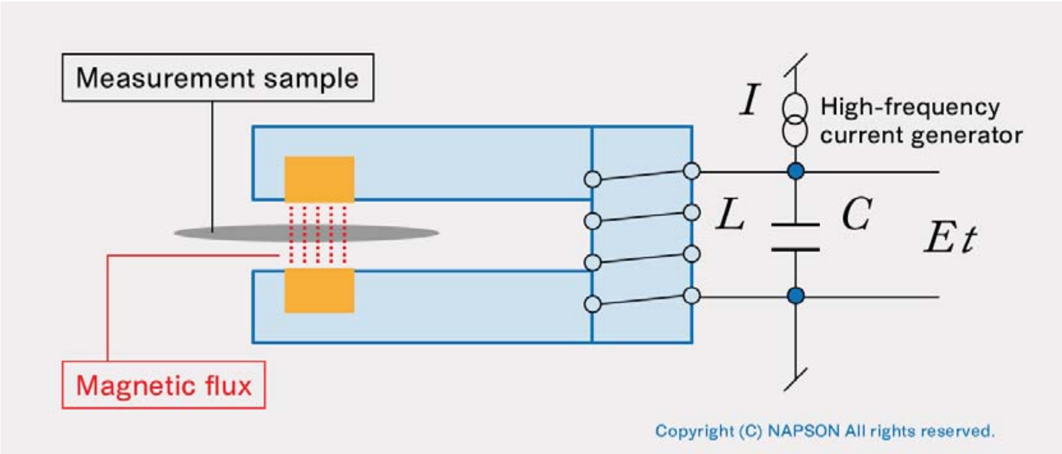
Eddy-current method can measure 1E-3 (1m) ~ 1E + 4 (10k) Ω / □ level of resistance range.
It is used to measure the sample such as semiconductor, FPD ,new materials & functional materials(CNT, DLC, grapheme, Ag nanowire etc).

Measurement system by eddy-current method measures the resistance by utilizing an eddy-current generated by electromagnetic induction.

Eddy-current method will be carried out measured by the following procedure.



The probe unit is composed of couple of probe cores(upside and downside) which is disposed between a fixed distance.

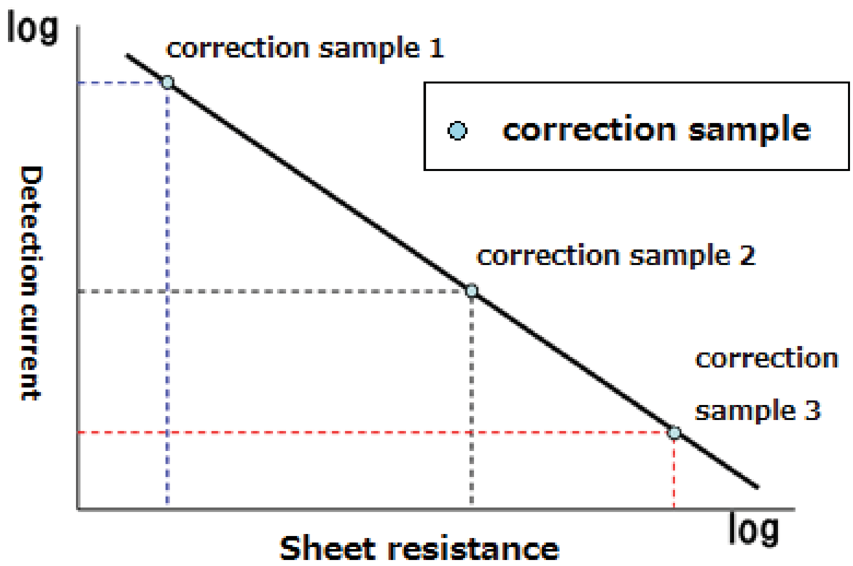


<1> Generating a magnetic flux by adding the high frequency between the probe core. When insert a sample to this magnetic flux, eddy current is generated in the sample. The eddy current will flow in the direction that prevents the change in the magnetic flux by the electromagnetic induction (Lenz's law).

<2> At this time,
1. An eddy current flows through the sample
2. Current is consumed within the sample, power attenuation occurs.
3. Current in the circuit is reduced in proportion to it. detect this reduced current value.

<3> Resistance of the detected current value is inversely proportional to the sample's resistance value.
By using this inverse relationship, Derive the sheet resistance(or resistivity) from the calculating formula(of the current value and sheet resistance).
(*To derive the resistivity, thickness information of the sample is needed.)

Please refer the case sample to make the calibration curve as following.
It needs to create a calibration curve that made of 3 kinds of calibration sample with a known resistance value.



Calibration curve (by sheet resistance & detection current)

Therefore,
- **Detected current value is high = Sheet resistance value is high**
- **Detected current value is low = Sheet resistance value is low**

8. <Non-contact type> Pulse excitation

This paragraph describes the non-contact resistance measurement principle by pulse voltage excitation method which used in the case of non-contact measurement of ultra-low-resistance range.

Pulse voltage excitation method can measure 1E-5(10μ)～1E-2(10m)Ω/□ level of resistance range.
It is used to measure the sample such as electrical conducting material, especially metal material & metal film.

Measuring principle of the pulse voltage excitation method is the following.
1. Gives the magnetic field changes from the DC magnetic field (single pulse).
2. Causes the power attenuation due to eddy currents.
3. Convert to sheet resistance by detected power attenuation.
(*Measurement principle is basically same as eddy current method.)

The probe unit is composed of couple of probe cores(upside and downside) which is disposed between a fixed distance(Same as eddy current method).
It raises an eddy current by applying a magnetic field to the sample from 1st circuit(Core 1).

At that time, 2nd circuit(Core2) detects Joule loss that occurs in the sample.
The sheet resistance value calculate by the calibration curve that made of inversely proportional relationship of Joule loss & sheet resistance.

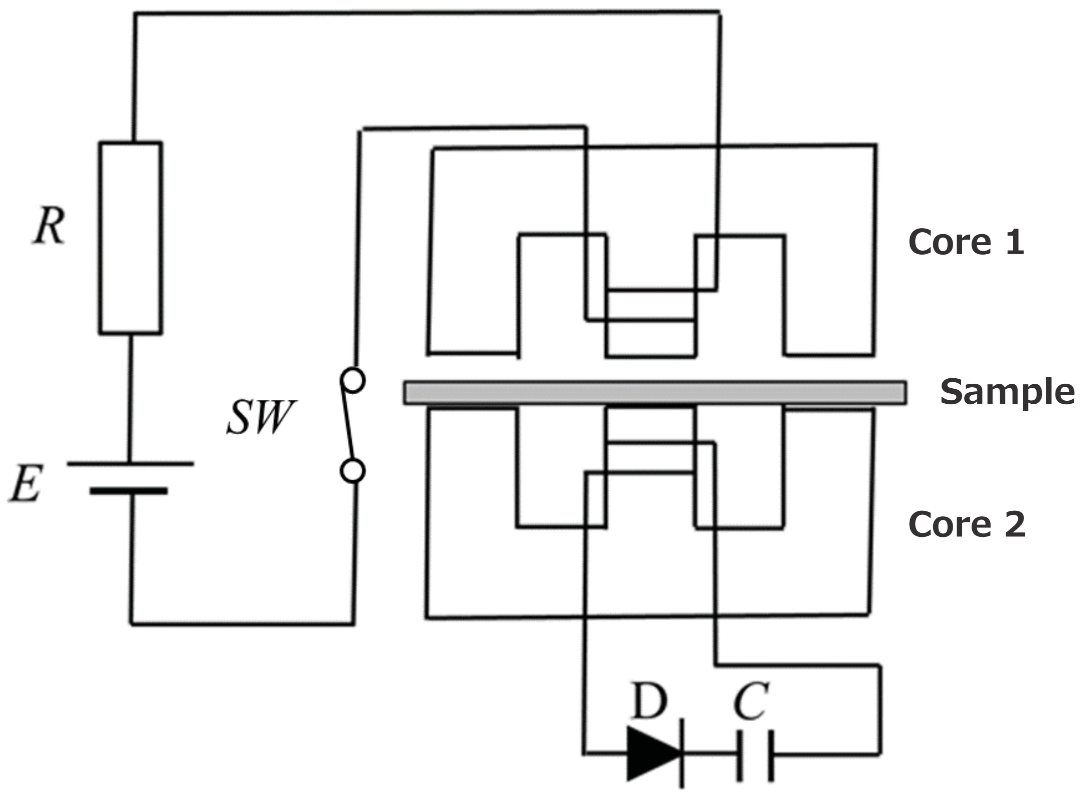


Fig 1 . Pulse excitation / Sheet resistance Overview figure

This section describes the measurement flow for culicurate the sheet resistance by pulse voltage excitation method.

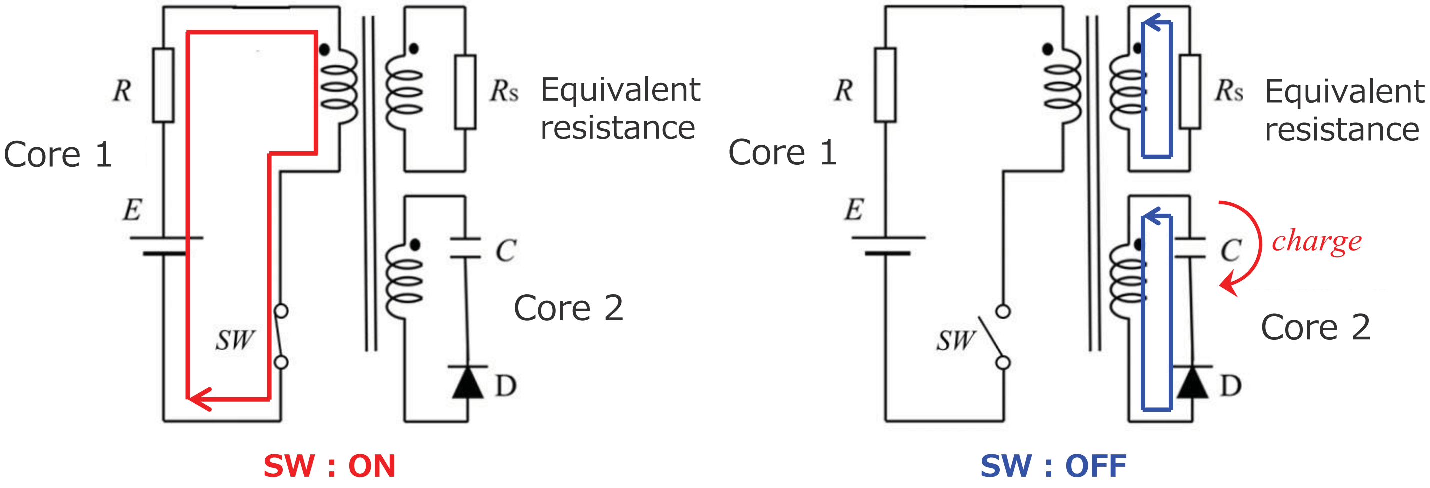
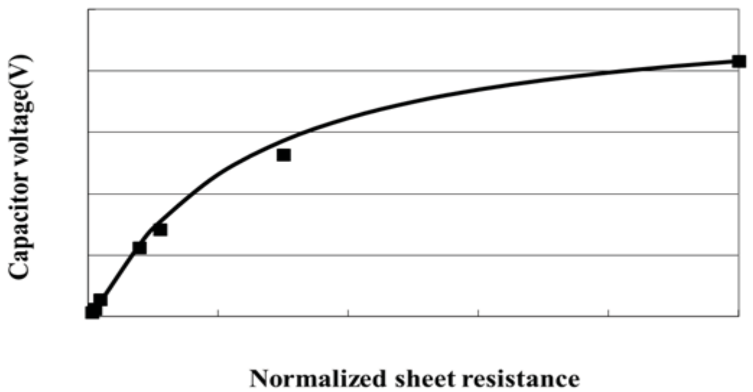


Fig 2． Pulse excitation / Sheet resistance measurement system
Equivalent circuit schematic

1. Turn on the switch, DC current flows the winding wire of the primary circuit(Core1) .
2. From the state of items 1, Momentarily turn off the switch.
3. When the switch turns off, Magnetic flux that passing through the sample is reduced rapidly and eddy current is generated in the sample.
4. At the same time as item 3, current will also occur in the winding wire of the secondary circuit(Core2).
5. Capacitors in the circuit (C) is charged by a current flowing through the winding wire of the secondary circuit(Core2).
6. There is a correlation about Sheet resistance value of the sample and Joule loss by eddy current.
   In addition, There is a correlation about Joule loss and charging voltage of the capacitor of secondary side circuit also.
   From these things, There is a correlation about sheet resistance value of sample and charging voltage of capacitor.
7. In advance, create a calibration curve of correlation about charging voltage and sheet resistance by calibration samples(which known sheet resistance value).
   Sheet resistance value of unknown sample will calculated from measured charging voltage by this calibration curve.



Sample; calibration curve about sheet resistance and charging voltage.

9. <Non-contact type> Electrostatic bond

This paragraph describes non-contact resistance measurement principle by electrostatic bond method.

Electrostatic bond method can measure 1E+3(1k)～1E+8(100M)Ω/☐ level of resistance range.
It is used to measure the sample which has high level sheet resistance range(higher level than eddy current method).

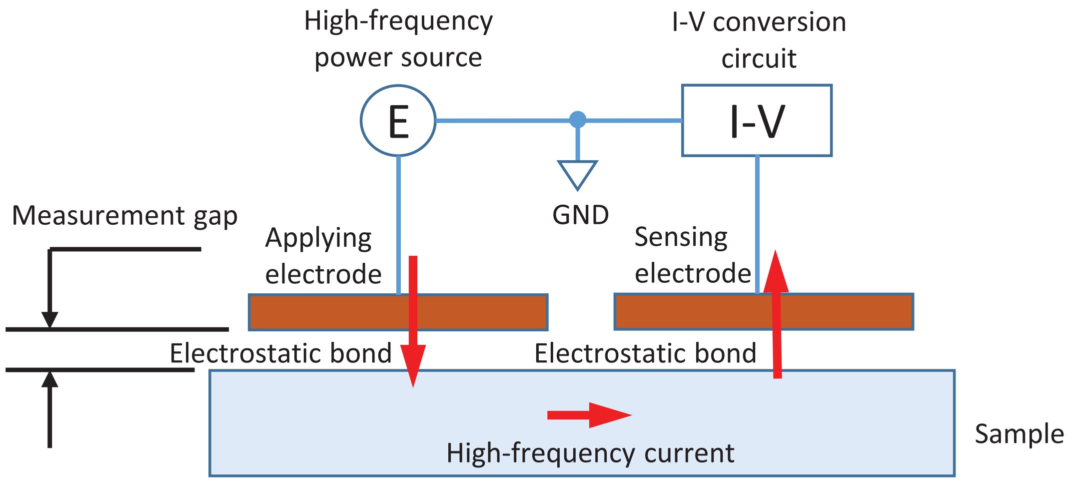


Fig 1. Electrostatic bond method ; General description
Sheet resistance measurement system

Electrostatic bond method makes use of electrostatic bond occurring when brought into opposing electrode and the sample(Capacitor is formed between the electrodes and the sample).
Flowing a high frequency current to the sample by electrostatic bonds.
Measure the sheet resistance of the sample by measuring the flowed high-frequency current.

The electrode and the sample places opposed as shown in FIG.
The application electrode to apply a several MHz RF voltage.
High-frequency current which inversely proportional to the sheet resistance of the sample flows through impressed electrode - sample - sensing electrode - I-V conversion circuit by the electrostatic bond of electrode and sample.

Convert the high-frequency current to DC voltage signal at the I-V conversion circuit.
In advance, create a calibration curve of correlation about DC voltage and sheet resistance by calibration samples(which known sheet resistance value).
Sheet resistance value of unknown sample will calculated from measured DC voltage by this calibration curve.

This section describes the measured flow of sheet resistance measurements by high-frequency electrostatic coupling method.

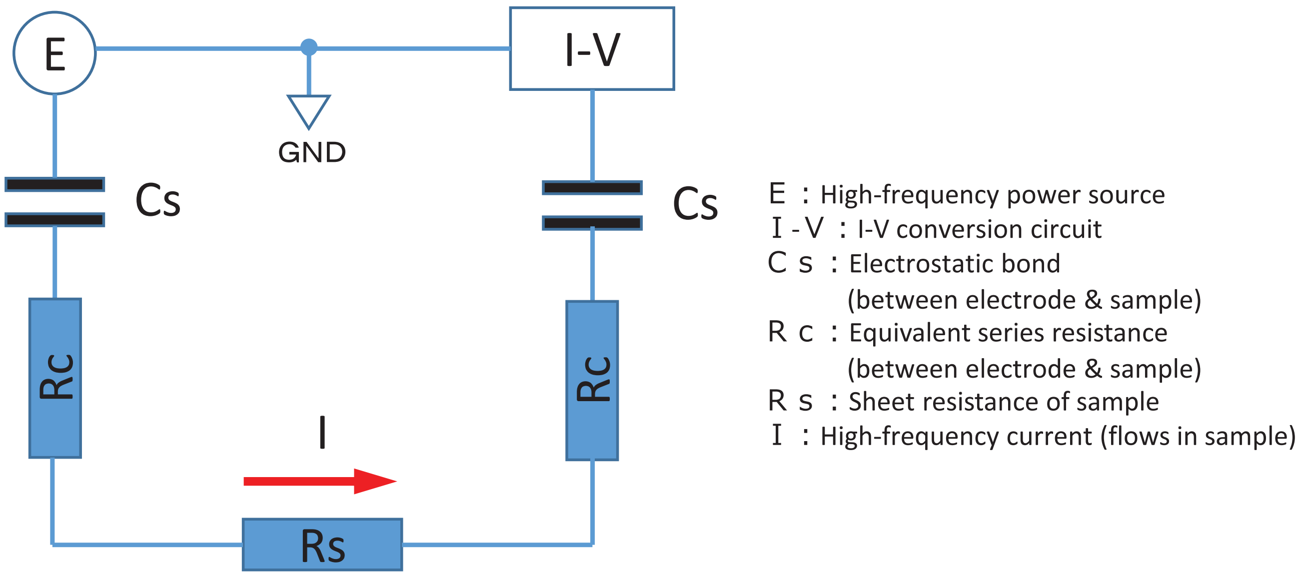


Fig 2． Electrostatic bond method ; Analogous circuit

1. Electric bond occurs between electrode & sample which placed opposed as shown in Fig 2. In this state, high-frequency voltage is applied to the applying electrode.
2. High-frequency current which inversely proportional to the sheet resistance of the sample flows through impressed electrode - sample - sensing electrode - I-V conversion circuit by the electrostatic bond of electrode and sample.
3. High-frequency current flowing through the sample, if the capacitance is constant, will be something that is inversely proportional to the sheet resistance of the sample.
4. Convert the high-frequency current to DC voltage signal at the I-V conversion circuit. In advance, create a calibration curve of correlation about DC voltage and sheet resistance by calibration samples(which known sheet resistance value).

   Sheet resistance value of unknown sample will calculated from measured DC voltage by this calibration curve.

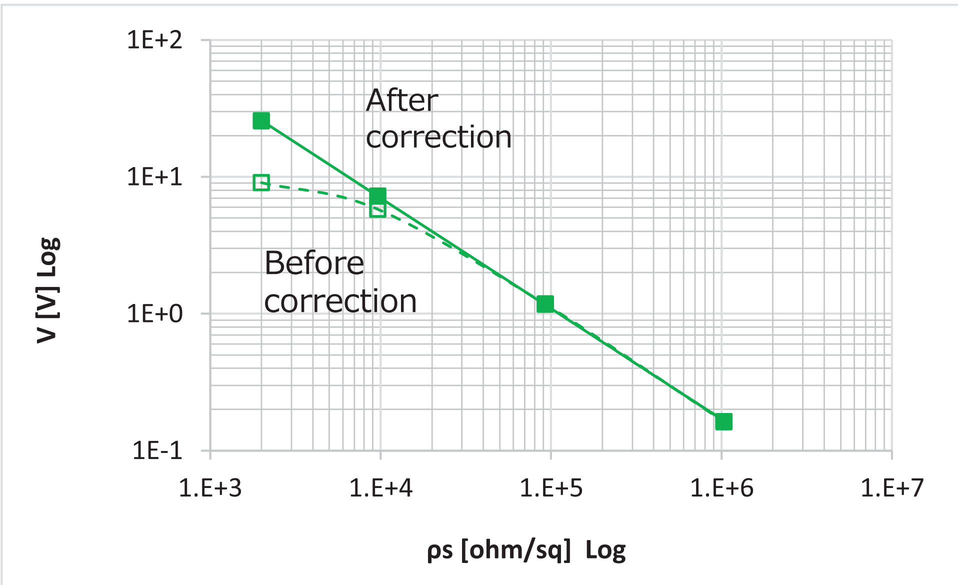
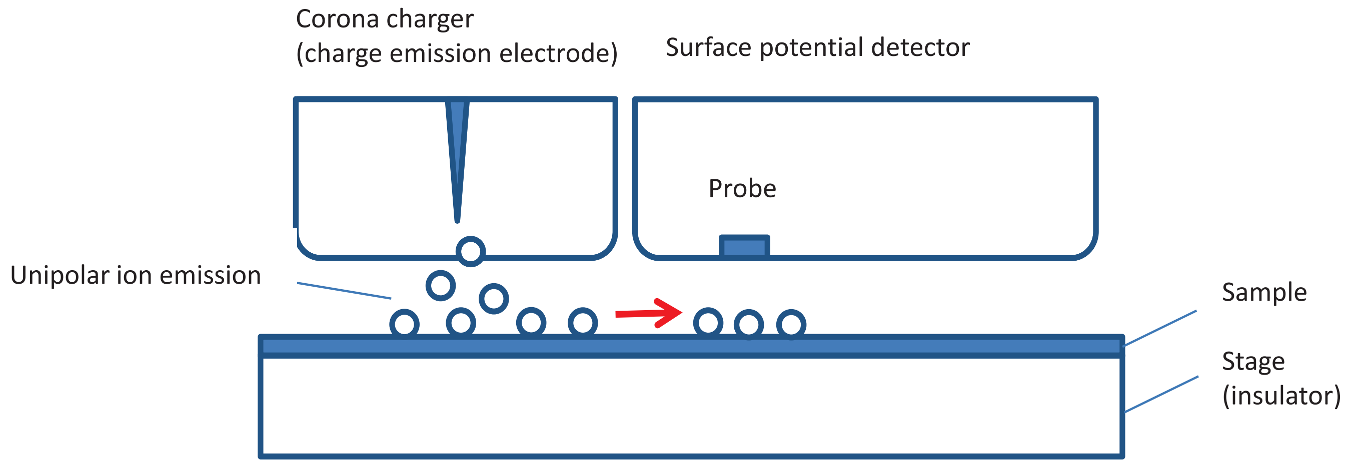


Fig 3． Sample; calibration curve (Thin film on glass)

10. <Non-contact type> Corona discharge

This paragraph describes non-contact resistance measurement principle by corona discharge method.

Corona discharge method can measure 1E+8(100M)〜1E+15(1P)Ω/☐ level of resistance range.
As with 2 probe method, it is used for the measurement of Super High resistance range.
There are merits by non-contact measurement;
Not affected by the contact resistance, Can use for viscous things(adhesion bond etc).



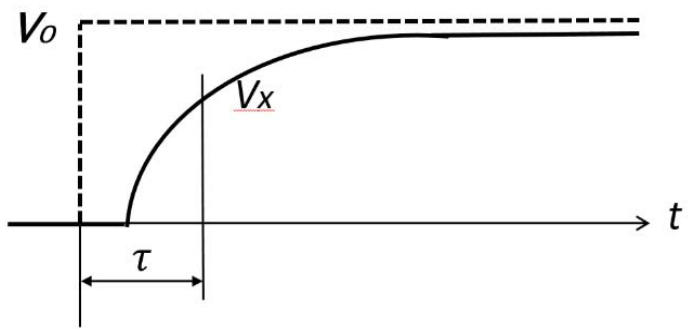
1. Unipolar ions are generated from the corona charger [Measurement start].
2. Unipolar ions generated will continue to adhere to the sample surface.
3. The electrification charge will continue to move to a low potential location from high potential location of the sample surface.
4. Surface potential distribution (movement time of electrifriction charge) is detected by a surface potential detector.
5. Since the surface potential distribution is dependent on the surface resistance value, it can be used to estimate the surface resistance by measuring the surface potential.

The surface potential V (x, t) is shown as following calculating formula by t seconds after the start of measurement by distance between x position from start position(under the corona charger) .

$$V(x,t) = V_0\left(1 - erf\left(\sqrt{\frac{\varepsilon\rho_s}{4t\delta}}x\right)\right)$$

V_0 : Surface potential of start position (under the corona charger)
Vx : Surface potential of x position
δ : Gap between the ground electrode (detector outer periphery) and the detector surface
x : distance of x position (from start position to detector position)
ρs : Sheet resistance of sample
ε : Dielectric constant of sample
erf : Error function of Gaussian

This paragraph describes the response characteristics between the surface potential of start position(under the corona charger) [V_0] & Surface potential of X position [Vx].



(time change of V_0 & Vx)

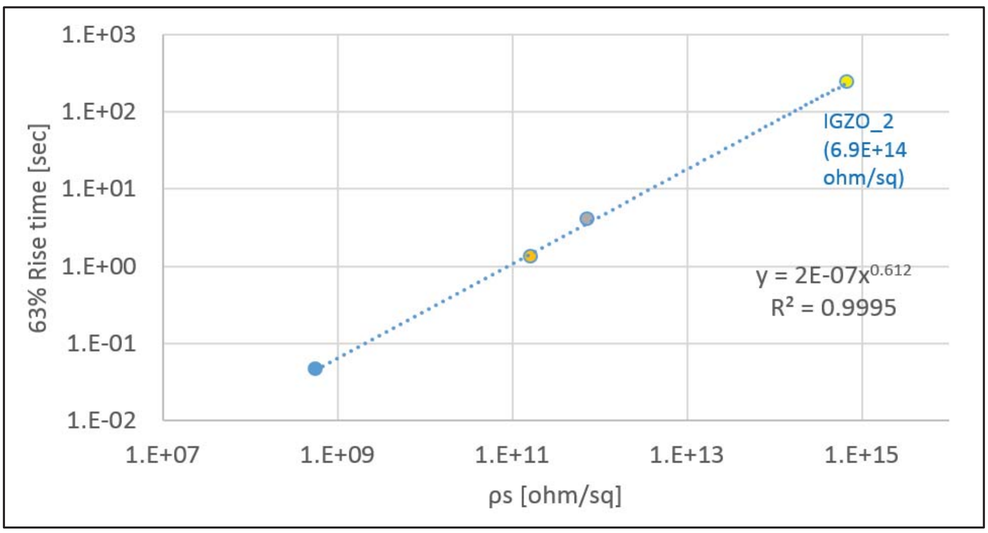
τ : Rising time of up to a predetermined potential
(During Switch ON ~ Vx)

Make calibration curve of the rising time & sheet resistance by using the standard sample of sheet resistance.

* Sample as a reference is determined based on the sheet resistance value measured by other measurement methods.
(Such as a ring probe 2 probe and the four-probe method).

Therefore, the accuracy of the absolute value of the sheet resistance by the corona discharge method is dependent on the reference sample to be used for calibration.

The sample which sheet resistance value is unknown, measure the rising time by corona discharge method to calculate the sheet resistance value from a calibration curve.



(Calibration curve ; Rising time / Sheet resistance)

*Corona Discharge Method : Pat. No.5510629 Joint development with Yamagata Univ.
(Associate Professor : Dr. Toshiyuki Sugimoto)

*The contents are subject to change without notice.

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