Development of a Handheld Sheet Resistance Meter with the Dual-configuration Four-point Probe Method

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Abstract – A handheld sheet resistance meter that can easily and quickly measure the sheet resistance of indium tin oxide films was developed. The dual-configuration four-point probe method was adopted for this instrument, which measured sheet resistance in the range from 0.26 $\Omega/\text{sq.}$ to 2.6 $\text{k}\Omega/\text{sq.}$ with 0.3 % ~ 0.5 % uncertainty. The screen of the instrument displayed the sheet resistance when the probe was in contact with the sample surface and the value continued to be displayed during the probe contact. Even after separating the probe from the surface, the value was still displayed on the screen and could be read easily. A feature of the instrument was the use of the dual-configuration technique to reduce edge effects markedly compared with the single-configuration technique and its ease of operation without applying correction factors for sample size and thickness.

Keywords: Four-point probe method, Single & dual configuration, Col-linear four point probe, Resistance, Resistivity, Sheet resistance, Silicon wafer, Linearity, Accuracy, Uncertainty

1. Introduction

The sheet resistance of indium tin oxide (ITO) films, which are used for transparent electrodes of touch panels and touch screens in smart phones and tablet PCs, is very important for product design.

The four-point probe (FPP) method with single or dual configuration is widely used to measure sheet resistance [1-6]. In the single-configuration technique, sample size and thickness corrections should be applied against probe spacing and in the dual-configuration technique, such corrections are not needed [7, 8]. At present, the handheld sheet resistance meters for sheet resistance measurements of thin films adopt the single-configuration technique. Thus, they have large edge effects and are inaccurate because only $\pi/\ln 2$ is used as the correction factor for sample geometry.

Recently, there is an essential need to develop instruments that overcome these disadvantages and are easy to operate. In this study, we developed a handheld sheet resistance meter with the dual-configuration technique. It featured automatic measurements of sheet resistance when its probe touched the thin film surfaces and it had the least edge effects. It had functions to measure resistance and sheet resistance and linearity, stability, and reproducibility.

The repeatability and accuracy for such functions were evaluated by standard resistors, decade resistances, and sheet resistance-certified reference materials (CRMs), which are traceable to the Korea Research Institute of

Standards and Science (KRISS), the national metrology institute of the Republic of Korea.

2. Four-Point Probe (FPP) Method

2.1 Single configuration

The single-configuration technique determines sheet resistance by measuring the resistance when contacting a collinear FPP on a sample surface and after applying sample size and thickness correction factors against probe spacing [3-5]. As shown in Fig. 1(a), the resistance R_s is determined by applying current I_{AD} between the probes A and D and measuring the voltage V_{BC} between the probes B and C , and is given by the following formula.

$$R_s = V_{BC}/I_{AD} [\Omega] \quad (1)$$

From the resistance, the sheet resistance by the single-configuration technique is given by

$$R_{ss} = k_s \times R_s [\Omega/\text{sq.}] \quad (2)$$

Here, k_s is a correction factor and is given by:

$$k_s = F(D/S) \times F(t/S) \times F(T) \times F(S) \quad (3)$$

From Eq. (3), $F(D/S)$ [1-5] is a correction factor for sample size D against probe spacing S . The correction factors for circular and rectangular samples are shown in Figs. 2 and 3 and are summarized in Table 1. In Table 1, $F(D/S)$ is equal to 4.5324 or $\pi/\ln 2$ if D/S is infinite, and for finite D and S , it is determined by applying Table 1.

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Table 1. Correction factors for sample size against the probe spacing; $F(D/S)$

D/S	Circular shape	Rectangular shape			
		$a/D=1$	$a/D=2$	$a/D=3$	$a/D \geq 4$
1.0	-	-	-	0.9988	0.9994
1.25	-	-	-	1.2467	1.2248
1.3	-	-	1.4788	1.4893	1.4893
1.75	-	-	1.7196	1.7238	1.7238
2.0	-	-	1.9454	1.9475	1.9475
2.5	-	-	2.3532	2.3541	2.3541
3.0	2.2662	2.4575	2.7000	2.7005	2.7005
4.0	2.9289	3.1137	3.2246	3.2248	3.2248
5.0	3.3625	3.5098	3.5749	3.5750	3.5750
7.5	3.9273	4.0095	4.0361	4.0362	4.0362
10.0	4.1716	4.2209	4.2357	4.2357	4.2357
15.0	4.3646	4.3882	4.3947	4.3947	4.3947
20.0	4.4364	4.4516	4.4553	4.4553	4.4553
40.0	4.5076	4.5120	4.5129	4.5129	4.5129
∞	4.5324	4.5324	4.5324	4.5325	4.5321

Table 2. Correction factors for sample thickness against the probe spacing; $F(t/S)$

$F(t/S)$	t/S
1.0000	0.100
1.0000	0.141
1.0000	0.200
0.9999	0.333
0.9974	0.500
0.9215	1.000
0.7983	1.414
0.6337	2.000
0.4067	3.333
0.2753	5.000
0.1385	10.00

Fig. 1. Four-point probe method

In addition, $F(t/S)$ [1-5] is a correction factor for sample thickness t against probe spacing S and is shown in Table 2.

If S is 1.00 mm and t is 0.200 mm, $F(t/S)$ is equal to 1.000. Generally, the correction factor applied for the sheet resistance of conducting thin films is 1.0. $F(T)$ is the temperature correction factor for the measurement environment and if the measurement temperature is $(23.0 \pm 0.5)^\circ\text{C}$, it is equal to 1.0 because $F(T) = 1 - C_T(T - 23)$. In addition, $F(S)$ is the correction factor for probe spacing

Fig. 2. Sample of a circular shape

Fig. 3. Sample of a rectangular shape

and is expressed as $F(S) = 1 + 1.082 \times (1 - S_2/S)$ in a linear approximation. If S_2 is equal to S , it is equal to 1.000.

2.2 Dual Configuration

This technique is used to determine sheet resistance using the resistance R_s , which is given from the formula Eq. (1) and the resistance R_d , which is obtained by applying current I_{AC} between the probes A and C and measuring the voltage V_{BD} between the probes B and D, and it is finally given by the following formulas Eq. (4) and Eq. (5) [6, 7].

$$R_d = V_{BD}/I_{AC} [\Omega] \quad (4)$$

$$R_{sd} = k_d \times R_s [\Omega/\text{sq.}] \quad (5)$$

Here, the sheet resistance identified by the dual-configuration technique and the constant is given by

$$k_d = -14.696 + 25.173(R_s/R_d) - 7.872(R_s/R_d)^2 \quad (6)$$

where the ratio R_s/R_d should be $1.20 \leq R_s/R_d \leq 1.32$.

3. Design and Manufacture of the Sheet Resistance Meter

3.1 Meter assembly

As shown in Fig. 4, the meter consists of a power unit, an arithmetic unit, a display unit, an A/D converter, a gain amplifier, a current source unit, a FPP, and a rechargeable

Fig. 4. Block diagram of the developed sheet resistance meter

Fig. 5. Measuring chart for a sheet resistance

Fig. 6. The developed handheld sheet resistance meter and its probe station

battery. It has functions to measure resistance and sheet resistance. When its probe contacts the sample surface vertically the sheet resistance is displayed on the screen and the reproducibility, stability, and repeatability of measurement value can be evaluated because the value is continuously displayed during the contact. The sheet resistance value can be easily and simply read because the last measured value is displayed on the screen even after the probe is separated from the surface. Fig. 5 shows the measurement procedure for sheet resistance by the developed sheet resistance meter.

3.2 Probe station and probe head

The probe station was designed to minimize the contact effects produced by the probe wandering on measurement. It features fixing probe heads, controlling weights,

Fig. 7. The developed four-point probe

Fig. 8. Standard resistors and a decade resistor

moving the probe head upward and downward and installing a rotator to measure sheet resistance at arbitrary measurement positions. Fig. 6 depicts the assembly of the developed sheet resistance meter, FPP, probe station, balance weights, handling holder, rotator, sheet resistance standards, and ITO thin films. Several types of the probe were made to correspond with the various sample types (Fig. 7). The probe pins were made of tungsten carbide and brass, which has good durability and stability. The probe spacing, force, and tip radius were 1.00 mm, 100 g, and 150 μm and 350 μm , respectively. The probes shown in Fig. 7(1) and 7(3) are models attaching to the designed probe station and those shown in Fig. 7(2) and 7(4) are models to measure sheet resistance at target sites on a sample while holding them. To confirm the probe performance, we used the developed probes and commercial Jandel probes to measure the sheet resistance of the CRMs and the two results were in good agreement.

3.3 Performance evaluation of the developed sheet resistance meter

The performance of the developed sheet resistance meter was evaluated using the KRISS-traceable standard resistors (IET series), a decade resistor (ESI DB62) and the sheet resistance CRMs as depicted in Fig. 8. We evaluated key parameters of the meter, such as linearity, reproducibility, repeatability, stability, and the sheet resistance function.

The linearity evaluation of the resistance and sheet resistance function were carried out by measuring and averaging out the resistance of the meter 10 times for each

Table 3. Linearity characteristics for the resistance function

Std. applied value (Ω)	Meter display (Ω)	Uncertainty (Ω) ($k = 2$)
0.1000	0.100	0.001
0.2000	0.200	0.001
0.3000	0.300	0.001
0.5000	0.500	0.001
0.7000	0.700	0.001
1.0000	1.000	0.001
2.000	2.00	0.01
3.000	3.00	0.01
5.000	5.00	0.01
7.000	7.00	0.01
10.000	10.00	0.01
20.000	20.00	0.01
30.00	30.0	0.1
50.00	50.0	0.1
70.00	70.0	0.1
100.00	100.0	0.1
200.00	200.0	0.1
300.0	300	1
400.0	400	1
500.0	500	1
700.0	700	1
1000.0	1000	1

Table 4. Step resistance characteristics for the resistance measurement function

Std. applied value (Ω)	Display (Ω)	Uncertainty (Ω) ($k = 2$)
10.000	10.00	0.01
10.100	10.10	0.01
10.010	10.01	0.01
11.000	11.00	0.01
11.100	11.10	0.01
11.110	11.11	0.01

Fig. 9. Diagram for evaluation of linearity characteristics

previously calibrated resistance value of a decade resistor between 0.1Ω and $1 \text{ k}\Omega$, as shown in Fig. 9.

The results are shown in Table 3. The uncertainty in the resistance measurements was estimated to be 0.1% at $k = 2$ for the full range of 1Ω , 10Ω , 100Ω , and $1 \text{ k}\Omega$ according to the ISO/IEC Guide [9]. Fig. 10 shows the linearity property for the resistance function of the developed meter. The reproducibility and repeatability evaluation was carried out by setting an arbitrary value of the decade resistor and measuring the value more than 10 times and the results agreed within 0.1% . The stability was given as ± 1 digit for $31/2$ digit resolution. Table 4 shows the evaluation results for steps resistance properties of the resistance function and means meter display value for

Table 5. Sheet resistance characteristics of the developed sheet resistance meter

Range	Std. Applied value ($\Omega/\text{sq.}$)	Meter display ($\Omega/\text{sq.}$)	Uncertainty ($\Omega/\text{sq.}$) ($k = 2$)
1	0.2605	0.261	0.001
	1.3030	1.303	0.001
	5.220	5.21	0.01
	10.431	10.43	0.01
2	13.035	13.04	0.01
	18.247	18.25	0.01
	20.85	20.8	0.1
	26.05	26.1	0.1
	52.12	52.1	0.1
	104.22	104.2	0.2
3	130.28	130.3	0.1
	182.38	182.4	0.1
	260.5	261	1
	521.0	521	1
	781.5	782	1
	1.042 k	1.042 k	0.002 k
	1.303 k	1.303 k	0.002 k
	2.605 k	2.61 k	0.01 k

Fig. 10. Linearity characteristics for the developed sheet resistance meter

reference resistance value and the results show the same property for all measurement ranges of the meter. We confirmed the performance of the sheet resistance function through the formulas Eq. (5) and Eq. (6). First, as shown in Fig. 9, connect the standard resistor 0.1000Ω with a four-terminal structure to the probe input terminals (A , B , C , D) of the meter. Second, measure the resistances R_s and R_d shown in Fig. 1(a, b). Then, the ratio of resistance values R_s to R_d is equal to 1.000 and the sheet resistance constant k_d is given the value 2.605 in the dual-configuration technique by formula Eq. (6). Therefore, from formula Eq. (5), R_{sd} is theoretically $0.2605 \Omega/\text{sq.}$ and if this value is displayed on the meter, the validity of the sheet resistance function is confirmed. By the same method, if a standard resistor of 1.0000Ω , 10.000Ω , 100.00Ω , or $1.0000 \text{ k}\Omega$ is connected to the probe input terminals of the meter (A , B , C , D) and measured, the theoretical sheet resistance value would be $2.605 \Omega/\text{sq.}$, $26.05 \Omega/\text{sq.}$, $260.5 \Omega/\text{sq.}$ or $2.605 \text{ k}\Omega/\text{sq.}$, respectively. Table 5 shows the results that confirmed the sheet resistance property for each range using the standard resistors and the decade resistor. Table 6 outlines the evaluation results of the properties of the

Table 6. Sheet resistance characteristics using the sheet resistance CRMs

Sheet resistance CRMs.	Meter display	Uncertainty ($k = 2$)
10.075 $\Omega/\text{sq.}$	10.08 $\Omega/\text{sq.}$	0.03 $\Omega/\text{sq.}$
103.8 $\Omega/\text{sq.}$	103.9 $\Omega/\text{sq.}$	0.3 $\Omega/\text{sq.}$
1058.3 $\Omega/\text{sq.}$	1056 $\Omega/\text{sq.}$	5 $\Omega/\text{sq.}$

Table 7. Sheet resistance characteristics using the ITO samples

ITO sample value ($\Omega/\text{sq.}$)	Meter display ($\Omega/\text{sq.}$)	Uncertainty ($k = 2$) ($\Omega/\text{sq.}$)
55.40	55.4	0.2
243.0	243	1
477.0	476	2

Fig. 11. Comparison of edge effects by the single- and dual-configuration FPP method **Fig. 12.** Measuring positions and directions

meter using the sheet resistance CRMs (10 $\Omega/\text{sq.}$, 100 $\Omega/\text{sq.}$ and 1000 $\Omega/\text{sq.}$) with measurement uncertainty of 0.3 %–0.5 %. From the results, it is confirmed that the developed meter has superior performance by comparison with currently-available meters with single-configuration method. In addition, Table 7 summarizes the measurement results for sheet resistance of ITO samples (55 $\Omega/\text{sq.}$, 243 $\Omega/\text{sq.}$ and 477 $\Omega/\text{sq.}$).

The measurements were performed within a diameter of 10 mm of the sample center with 1.0 mm steps and at an angle of 45°. After performing 10 measurements at each

site, the average values and standard deviations were obtained for a total of 40 measurements and then the measurement uncertainty was estimated.

3.4 Comparison of edge effects by the single- and dual-configuration FPP method

Fig. 11 depicts the results for a sheet resistance CRM (10.075 $\Omega/\text{sq.}$) with a 125 mm diameter measured by the two methods with 1.0 mm steps from the sample edge to the sample center. The probe positions and measurement directions are shown in Fig. 12. The result obtained with the single-configuration method had a larger edge effect than the dual-configuration method. The former is the sheet resistance calculated from multiplying the measured resistance values by $\pi/\ln 2$, which is the correction factor for a handheld sheet resistance meter. The latter has almost the same sheet resistance for the entire region, as shown in Fig. 11. It can be verified that these results agree with the theoretical result. From Fig. 11, we can see that the sheet resistance by the single-configuration method presents an obvious edge effect from the sample edge to a 15 mm distance toward the sample center. Therefore, one should consider the edge effect when measuring with the single-configuration method.

4. Conclusion

We developed a handheld sheet resistance meter that can easily and quickly measure the sheet resistance of ITO films for touch panels and screens. A dual-configuration FPP method was adopted for the meter and it consists of a resistance function and a sheet resistance function.

The measurement range for the resistance function was from 0.1 Ω to 1.0 k Ω and the measurement range for the sheet resistance function was from 0.26 $\Omega/\text{sq.}$ to 2.6 k $\Omega/\text{sq.}$ The linearity, reproducibility, and stability properties of the resistance function were less than 0.1 % for the entire range and the measurement uncertainty for the sheet resistance function was between 0.3 % and 0.5 %. When the probe was in vertical contact with the sample surface, a value for the sheet resistance is displayed on the meter screen and the display is continued during the contact.

The sheet resistance value can be easily and simply read because the last measured value is displayed on the screen even if the probe is separated from the surface. In measuring with the single-configuration FPP method, correction factors for sample size and sample thickness against probe spacing should be applied.

In addition, we confirmed that the method had a large edge effect. In contrast, in measuring with the dual-configuration FPP method, there is no need to apply correction factors and the method has little edge effect. It is therefore considered that the meter developed in this study can be easily and simply used for sheet resistance

measurements of various conducting thin films including ITO.

References

- [1] Arther Uhler, JR, "The Potentials of Infinite Systems of Sources and Numerical Solutions of Problems in Semiconductor Engineering," *Bell System Technical Journal*, vol. 34, no. 1, pp. 105-128, 1955.
- [2] L. B. Valdes, "Resistivity Measurements on Germanium for Transistors," *Proceedings of the Institute of Radio Engineers New York*, vol. 42, pp. 420-427, Feb. 1954.
- [3] F. M. SMITS, "Measurement of Sheet Resistivities with the Four-Point Probe," *Proceedings of the Institute of Radio Engineers*, pp. 711-718, May 1958.
- [4] ASTM F84, "Standard Test Method for Measuring Resistivity of Silicon Wafers with an In-Line Four-Point Probe."
- [5] Lydon J. Swartzendruber, "Correction Factor Tables for Four-Point Probe Resistivity Measurements on Thin, Circular Semiconductor Samples," *NBS technical note* 199, April 1964.
- [6] ASTM F1529-97, "Standard Test Method for Sheet Resistance Uniformity Evaluation by In-Line Four-Point Probe with the Dual-Configuration Procedure," 1997.
- [7] J. R. Ehrstein and M. C. Crparlom, The Certification of 100 mm Diameter Silicon Resistivity SRMs 2541 through 2547 Using Dual-Configuration Four-Point Probe Measurements," *NIST Special Publication* 260-131, 1999.
- [8] Masato YAMASHITA, "Resistivity Measurement by Dual-Configuration Four-Probe Method," *The Japan Society of Applied Physics*, vol. 42, no. 2A, pp 695-699, February 2003.
- [9] ISO/IEC Guide 98-3, 2008(E) "Part 3: Guide to the Expression of Uncertainty in Measurement(GUM)," 1995.
- [10] EA-4/02, "Expression the uncertainty of measurement in calibration," 1999.
- [11] UKAS, M3003, "The Expression of Uncertainty and Confidence in Measurement," January 2007.

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