J Electr Eng Technol.2015;10(1): 325-330
http://dx.doi.org/10.5370/JEET.2015.10.1.325

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

An international Comparison Measurement of Silicon Wafer Sheet Resistance using the Four-point Probe Method

Jeon-Hong Kang*, Gao-Ying, Yuh-Chuan Cheng***, Chang-Soo Kim*, Sang-Hwa Lee* and Kwang-Min Yu†**

Abstract – With approval from the Asia Pacific Metrology Program Working Group on Materials Metrology (APMP WGMM), an international comparison for sheet resistance standards for silicon wafers was firstly conducted among Korea Research Institute of Standards and Science (KRISS) in Korea, CMS/ITRI in Taiwan, and NIM in China, which are national metrology institutes (NMIs), from August 2011 to January 2012. The sheet resistance values of the standards are 10 Ω, 100Ω, and 1000 Ω; the measurement was conducted in sequence at KRISS, CMS/ITRI, NIM, and KRISS again using the four-point probe method with single and dual configuration techniques. The reference value for the measurement results of the three NMIs was obtained through averaging the values of the three results for each sheet resistance range. The differences between the reference value and the measured values is within 0.22% for 10Ω, 0.17% for 100Ω, and 0.12% for 1000Ω. Therefore, the international consistency for conducting sheet resistance measurements is confirmed within 0.22% through the APMP WGMM approved comparison.

Keywords: Four-point probe method, Single & dual configuration, Collinear four point probe, Sheet resistance, Silicon wafer, Uncertainty.

1. Introduction

The Asia Pacific Metrology Program Working Group on Materials Metrology (APMP WGMM) meetings in which Korea Research Institute of Standards and Science (KRISS), Center for Measurement Standards/Industrial Technology Research Institute (CMS/ITRI), and National Institute of Metrology (NIM) participates have been held every year; these meetings focus on a variety of material standards and material evaluation techniques. In 2010, an international comparison in which three NMIs would participate was proposed at the meeting, and the sheet resistance standards for semiconductors were selected as the item for which the comparison would be conducted. Then, the first APMP WGMM comparison for sheet resistance standards in which KRISS, CMS/ITRI, and NIM participated was conducted between August 2011 and January 2012. The purpose of the comparison was to confirm international consistency and equivalence regarding the measurement results for sheet resistance. As is well known, precise measurement for electrical resistivity in silicon wafers is increasingly required with the rapid development of semiconductor industry. In addition, recently, the display industry related to cell phones and navigation devices has increased rapidly. Therefore, all meeting participants recognized that precise measurement for the sheet resistance of the conducting thin films that are used as transparent electrodes in touch panel and touch screen displays is essential. Furthermore, sheet resistance uniformity of indium-tin-oxide (ITO) and carbon nanotubes (CNTs) is directly related to product quality; thus, precise measurement and control of the sheet resistance is crucial. Accordingly, sheet resistance testers using a four-point probe (FPP) method were used to measure sheet resistances in semiconductor, touch panel, and touch screen processes. Commercial sheet resistance testers can adopt a contact FPP method and a noncontact eddy current method for measurement accuracy and material properties. However, measurement accuracy using a FPP method is generally more than five times superior to that using an eddy current method. The FPP method is divided into two techniques: a single configuration technique [1-6] and a dual configuration technique [7-9]. With the single configuration technique, the sample thickness and sample size correction factor against the probe spacing should always be applied in order to determine the sheet resistance [5, 6]. However, with the dual configuration technique, correction factors of the sample thickness and size effects are not applied and the edge effect is also very slight compared with the single configuration technique. All participants in this comparison used the FPP method with a single configuration or dual configuration technique, and the measurement positions

---

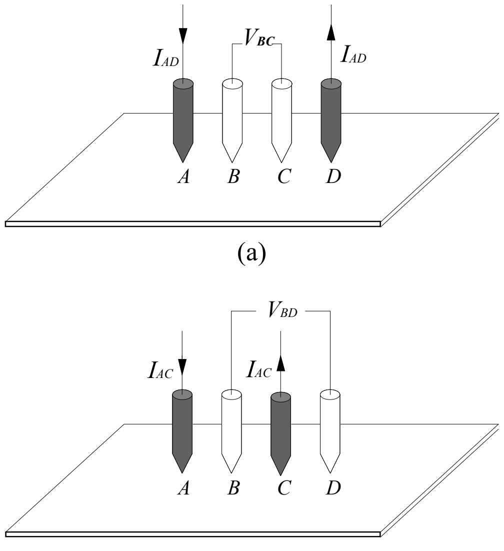
† Corresponding Author: Korea Research Institute of Standards and Science, Korea. (kmyu@kriss.re.kr)
* Korea Research Institute of Standards and Science, Korea. (jhkang, kimcs, shlee@kriss.re.kr)
** National Institute of Metrology (NIM), China. (gaoying@nim.ac.cn)
*** Center for Measurement Standards (CMS), Industrial Technology Research Institute (ITRI), Taiwan. (Vega_Cheng@itri.org.tw)
Received: June 12, 2014; Accepted: September 4, 2014

were limited to be within 10 mm of the sample center. The sheet resistance standards for the comparison were 10 Ω (model: KRISS-10, S/N: 2011-10), 100 Ω (model: KRISS-100, S/N: 2011-100), and 1000 Ω (Model: KRISS-1000, S/N: 2011-1000) provided by the piloting laboratory. In this article, the measurement systems, measurement traceabilities, and comparison results among the three NMIs are described.

2. Four-Point Probe (FPP) Method

2.1 Single configuration technique

In order to determine the sheet resistance using the single configuration technique, the four probes with collinear arrays contacted a sample surface as seen in Fig. 1(a), and the voltage (V_{BC}) between probes B and C were measured through passing a current (I_{AD}) between probes A and D. Then, the resistance (R_S) was calculated using Eq. (1) and the sheet resistance (R_{SS}) was determined from Eq. (2) through applying a sample thickness and sample size correction factor against the probe spacing, as described in Eq. (3).



(a)

(b)

Fig. 1. Four-point probe method.

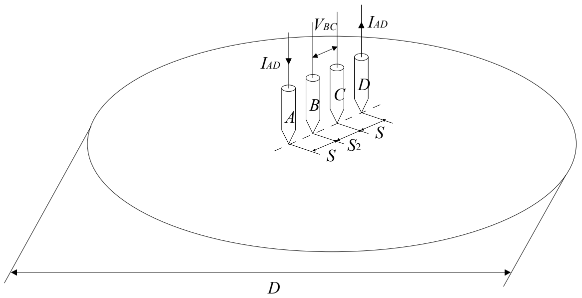


Fig. 2. Circular sample.

$$R_S = V_{BC}/I_{AD}\ [\Omega] \tag{1}$$

$$R_{SS} = k_S \times R_S\ [\Omega/\text{sq}] \tag{2}$$

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

$$k_S = F(D/S) \times F(t/S) \times F(T) \times F(S) \tag{3}$$

From Eq. (3), $F(D/S)$ is the correction factor for sample size D against the probe spacing S, and the values for circular(Fig. 2) and rectangular(Fig. 3) samples are described in Table 1 [1-5]. In the table, if the sample size is infinite, $F(D/S) = 4.5324$.

Furthermore, $F(t/S)$ is the correction factor for the sample thickness against probe spacing S and is described in Table 2 [1-5].

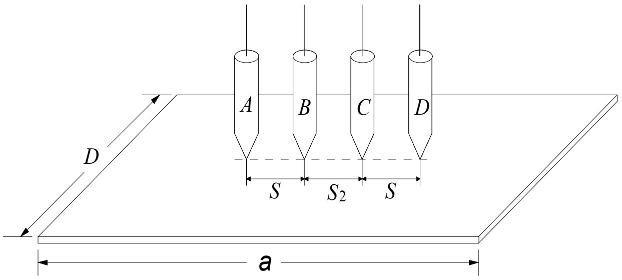


Fig. 3. Rectangular sample.

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

D/S	Circular sample	Rectangular sample			
		a/D=1	a/D=2	a/D=3	a/D≥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

If the probe spacing is equal to 1.00 mm and the thickness is less than 0.3 mm, $F(t/S)$ =1.000. Then, 1.000 is applied for a conducting thin film.

Moreover, $F(T)$ refers to the correction factor for the temperature and if the measurement temperature is 23.0 ±0.5°C, $F(T)$ is equal to 1.000 because $F(T) = 1 - C_T(T - 23)$. Furthermore, $F(S)$ [4] is the correction factor for the probe spacing and is given by $F(S) = 1 + 1.082 \times (1 - S_2/S)$. If it is assumed that S_2 is equal to S, then 1.000 is applied as the value.

2.2 Dual configuration technique

In order to determine the sheet resistance using the dual configuration technique, four probes contact collinear arrays on a sample surface as seen in Fig. 1(b), and the voltage (V_{BD}) between probes B and D is measured through passing a current (I_{AC}) between probes A and C. Then, the resistance (R_d) can be calculated using Eq. (4) and the sheet resistance (R_{Sd}) can be determined from the resistance (R_S) and a proportional constant (k_d) using Eq. (5).

$$R_d = V_{BD}/I_{AC}\ [\Omega] \tag{4}$$

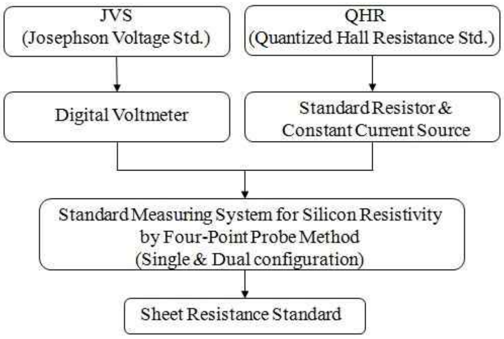
$$R_{Sd} = k_d \times R_S\ [\Omega/\text{sq.}] \tag{5}$$

Here, the proportional constant k_d [6-8] is given as follows:

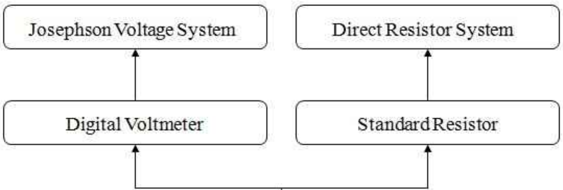
$$k_d = -14.696 + 25.173(R_S/R_d) - 7.872(R_S/R_d)^2 \tag{6}$$

where $1.20 \le R_S/R_d \le 1.32$ [6].

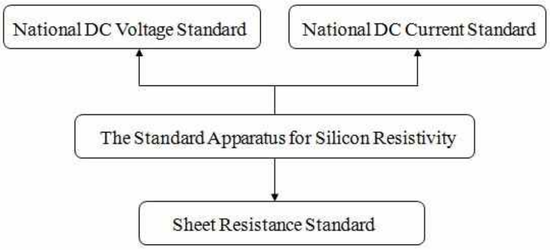
As shown in Eq. (5), R_{Sd} is determined using R_S and R_d, which are given by the two configurations and it is independent of geometrical effects.



(a) KRISS traceability system for sheet resistance standard



(b) CMS/ITRI traceability system for sheet resistance standard



(c) NIM traceability system for sheet resistance standard

Fig. 4. Traceability diagram for KRISS, CMS/ITRI, and NIM in the sheet resistance measurements.

3. Traceability System of Participants

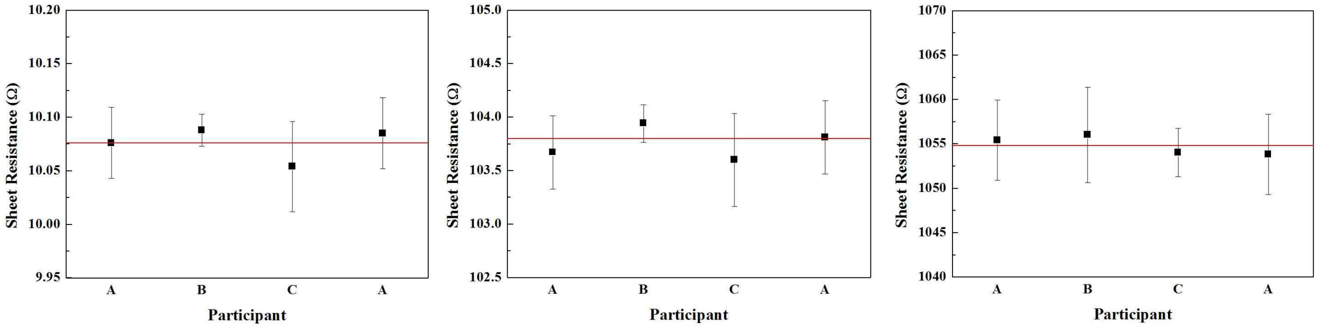
The traceability system of KRISS, CMS/ITRI, and NIM, who participated in the comparison, is presented in Fig. 4. The sheet resistance measured by each NMI is traceable to the national DC voltage standard, DC standard resistors, and digital voltmeter.

4. Stability, Temperature Coefficient and Light Effect of Sheet Resistance Standards

The sheet resistance standards for the international comparison were 15μm boron-doped N-type silicon wafers with 125mm in diameter and 0.625mm in thickness, and these had sheet resistances of 10Ω, 100Ω, and 1000Ω. The stability of the standards for six months between the starting time and finishing time of the comparison was evaluated to be less than 0.05% for 10Ω, less than 0.07% for 100 Ω, and less than 0.08% for 1000 Ω. Furthermore, the temperature coefficient was evaluated using the linear fitting of sheet resistances at 20°C, 23°C, and 26°C; this is demonstrated in the relative expression as 0.05% for 10 Ω, 0.07% for 100 Ω, and 0.37% for 1000 Ω. The light effect was also investigated using normal fluorescent lights and it gave no influence on 10 Ω. However, the influence was shown to be -1.5 % for 100 Ω and more than 4 % for 1000 Ω. Therefore, all measurements at this comparison were carried out at dark field and the light effect was negligible.

5. Measurement Results

The measurement results and measurement conditions are described in Table 3. KRISS used both single and dual configuration methods; CMS/ITRI used the dual configuration method; and NIM used the single configuration method. Table 4 presents the measurement results among three NMIs, which were all corrected to 23.0°C. The



(a) 10 Ω sheet resistance standard (b) 100 Ω sheet resistance standard (c) 1000 Ω sheet resistance standard

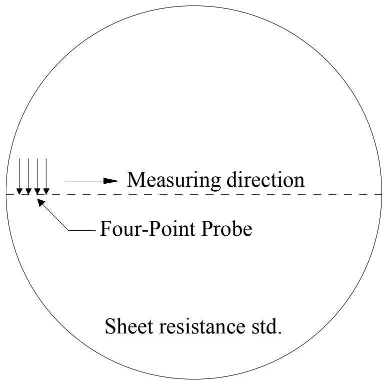
Fig. 5. Illustration of the measurement results of participants for the 10Ω, 100Ω, and 1000Ω sheet resistance standards.

Table 3. Measurement conditions.

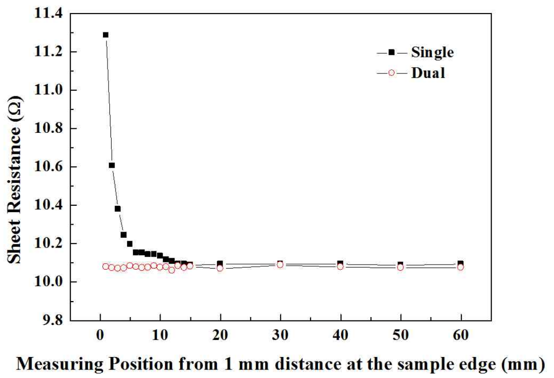
Parti.	Mea. method	Mea. Tem.	Ambient humidity	Test condition	Test current		
					10 Ω/sq.	100 Ω/sq.	1000 Ω/sq.
KRISS	Single & Dual	23.0℃	43 % R.H.	dark field	5mA	0.5mA	0.05mA
CMS/ ITRI	Dual	22.0℃	50 % R.H.	dark field	4mA	0.4mA	0.04mA
NIM	Single	23.0℃	30 % R.H.	dark field	5mA	0.5mA	0.05mA

Table 4. Measurement results for sheet resistance standards.

CRMs	Measurement results (Participant)				Average
	2011. 08. 10.	2011. 10. 03.	2011. 11. 23.	2012. 01. 02	
10 Ω/sq.	10.076	10.088	10.054	10.085	10.076
Uncertainty ($k = 2$)	0.33 %	0.15 %	0.42 %	0.33 %	
100 Ω/sq.	103.67	103.94	103.60	103.81	103.76
Uncertainty ($k = 2$)	0.33 %	0.17 %	0.42 %	0.33 %	
1000 Ω/sq.	1055.4	1056.0	1054.0	1053.8	1054.8
Uncertainty ($k = 2$)	0.43 %	0.51 %	0.26 %	0.43 %	



(a) Measuring position



(b) Measurement results by single & dual configuration

Fig. 6. Edge effect in the single configuration and dual configuration techniques.

measurements were conducted in the order of KRISS in August 2011, CMS / ITRI in October 2011, NIM in November 2011, and KRISS again in January 2012. In Fig. 5, the measurement results with uncertainties are depicted graphically for the 10Ω, 100Ω, and 1000Ω sheet resistance standards. In the graph, the reference values were taken by averaging the measurement results of the participants. The measurement uncertainty was estimated according to the ISO GUM Guide [10, 11], and it is expressed as expanded uncertainties at a 95% confidence level and a coverage factor of 2. Here, the uncertainty is estimated from type A and type B standard uncertainty. Type A standard uncertainty is given by the mean standard deviations, and type B standard uncertainty is given using the stability of the measuring instruments, temperature effects, and other information except the type A standard uncertainty by repeated measurements. From the graph, it is seen that all results from the participants had good agreement within the uncertainty in Table 4.

6. Discussion

In order to investigate the edge effect using the single configuration technique and dual configuration technique in the FPP method, the sheet resistances were measured with a position on a silicon wafer with a sheet resistance of 10 Ω and 1.0 mm probe spacing. As shown in Fig. 6, the edge effect is predominantly appeared within 5 mm from the edge of the wafer. Furthermore, in order to avoid carrier injections into the surface, an appropriate current is required and the measuring voltage to satisfy the condition is between 7 mV and 13 mV [7]. As shown in Table 3, all participants used appropriate currents and therefore the effect is not considered in this comparison. Moreover, because the free electrons in silicon can move actively with increasing light, thermal, and electrical energy, it is important to maintain the appropriate measurement temperature and humidity, as well as dark field conditions. In order to achieve this, a protocol for this comparison was constructed in order to specify the conditions; the conditions were satisfied for all participants.

7. Conclusion

An international comparison with the approval of the APMP WGMM was firstly conducted between August 2011 and January 2012 among KRISS, CMS/ITRI, and NIM. The travelling sheet resistance standards of silicon wafers were investigated, and a four-point probe method with single and dual configuration techniques were used to measure the sheet resistances of 10 Ω, 100 Ω, and 1000 Ω. The measurement results had agreement within 0.22% for 10 Ω, 0.17% for 100 Ω, and 0.12% for 1000 Ω from the average values and their expanded uncertainties were estimated to be between 0.15% and 0.51% with a coverage factor of 2. From the comparison results, an international equivalence and consistency for sheet resistance measurements was confirmed. Furthermore, the comparison was conducted as a piloting study and will be used for a formal key comparison of sheet resistances of semiconductors, which will be approved by the APMP WGMM and many NMIs will participate in the near future.

References

[1] Arther Uhlir, 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] E J Zimney, G H B Dommett, R S Ruoff and D A Dikin, "Correction factors for 4-probe electrical measurements with finite size electrodes and material anisotropy: a finite element study" Meas. Sci. Technol. 18 (2007), pp. 2067-2073, 2007.

[7] ASTM F1529-97, "Standard Test Method for Sheet Resistance Uniformity Evaluation by In-Line Four-Point Probe with the Dual-Configuration Procedure", 1997.

[8] 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.

[9] 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.

[10] ISO/IEC Guide 98-3, 2008(E) "Part 3: Guide to the Expression of Uncertainty in Measurement(GUM)", 1995.

[11] EA-4/02, "Expression the uncertainty of measurement in calibration", 1999.

Jeon-Hong Kang He received the M.S. degree in electrical engineering from Hanbat National University, Daejeon, Korea in 1998. He received the Ph.D. degree in electrical engineering from Chungnam National University, Daejeon, Korea, in 2008. From 1987 to present, he is currently working as a Senior Engineer at Center for Electricity and Magnetism of Korea Research Institute of Standards and Science (KRISS). His area of research interest is the evaluation of resistivity characteristics for metals, semiconductors and insulators.

Gao-Ying He was born in 1963 in China. He received the B.S. degree in electronic measurement technology from Beijing Union University, Beijing, China. In 1985, He joined the RF and Microwave Division, National Institute of Metrology (NIM), Beijing, where he is currently working with the measurement of Integrate Circuit in this area. Currently he is a Senior Engineer in NIM and Member of Subcommittee 2 on Semiconductor Material of National Technical Committee 203 on semiconductor devices and materials of Standardization Administration of China.

Yuh-Chuan Cheng She received the B.S. degree in electronic engineering from Chung Yuan Christian University in 1995 and the M.S. degree in institute of communications engineering from National Chiao Tung University in 2007. Currently, she is an associate Engineer in Center for Measurement Standards (CMS), Industrial Technology Research Institute (ITRI).

Chang-Soo Kim He received B.S. and M.S. degrees from Seoul National University, Korea, and completed Ph.D. degree in Materials Science at University of Connecticut, USA. He was a postdoctoral research fellow at the North Carolrina State University, USA from 1990 to 1991. Currently, he is working as a principal research scientist at Korea Research Institute of Standards and Science (KRISS). His area of research interest is materials metrology.

Sang-Hwa Lee He was born in 1967 in Korea. He received the B.S. degree in electronics from Hanbat National University, Daejeon, Korea, and the M.E. degrees in electrical engineering from Chungnam National University, Daejeon and he is currently working toward the Ph.D. degree. In 1985, he joined the Korea Research Institute of Standards and Science (KRISS), Deajeon, where he is currently working with ratio standards for direct and alternating-current (ac) high voltage and heavy ac applications and responsible for performing calibration services in those areas. Currently, he is a Principal Technician with the Center for Electricity and Magnetism, KRISS.

Kwang-Min Yu He was born in Busan, Republic of Korea, in 1960. He received the degree in physics from the Busan National University, Busan, Republic of Korea, in 1983, and the Ph.D. degree from Chungnam National University, Daejeon, Republic of Korea, in 2012. From 1986 to present, he was with the Korea Research Institute of Standards and Science (KRISS), as a Research Scientist. Here he is responsible for resistance measurement standard. His current main research interests are in high resistance measurements and technology.