Development and Evaluation of High-Stability Metal-Foil Resistor With a Resistance of 1 kΩ

Atsushi Domae, Takayuki Abe, Masaya Kumagai, Matsuo Zama, Takehiko Oe, *Member, IEEE*, and Nobu-hisa Kaneko

***Abstract*— Prototype models of a high-stability metal-foil resistor of 1 kΩ with a four-terminal-pair design were developed, and the key characteristics were evaluated. Two types of metal-foil resistors were fabricated: serial number (s/n) 1 is made from two resistor devices of 500 Ω and s/n 2 is made from three resistor devices of 333 Ω. To develop these resistor devices, a new resistor-device design was introduced. The s/n 1 resistor has the following key characteristics: drift rate: 0.010 ($\mu\Omega/\Omega$)/year, first-order temperature coefficient at 23 °C: −0.165 ($\mu\Omega/\Omega$)/°C, frequency dependence of the resistance (relative change in resistance normalized at 1 kHz): ±0.21 $\mu\Omega/\Omega$ in the frequency range from 400 Hz to 2 kHz, and time constant: −0.46 ns. The s/n 2 resistor has the following key characteristics: drift rate: −0.092 ($\mu\Omega/\Omega$)/year, first-order temperature coefficient at 23 °C: 0.096 ($\mu\Omega/\Omega$)/°C, frequency dependence of the resistance (relative change in resistance normalized at 1 kHz): ±0.54 $\mu\Omega/\Omega$ in the frequency range from 400 Hz to 2 kHz, and time constant: 0.12 ns.**

***Index Terms*— Drift rate, electrical resistance measurement, frequency dependence, measurement standards, phase-angle measurements, resistors, temperature dependence.**

I. Introduction

JAPAN Electric Meters Inspection Corporation (JEMIC), Alpha Electronics Corporation, and the National Metrology Institute of Japan (NMIJ) are collaborating to develop high-stability metal-foil resistors. It is known that mounting a resistor element in a stress-free manner is effective for maintaining a low drift rate as well as a low temperature coefficient of the resistor [1], [2] because the characteristics of the supporting material (the substrate) do not match those of the resistance element. However, commercially available film-type resistors are typically constructed by depositing a metal film with a thickness of 0.2 μm onto an insulating substrate. We instead adopted a resistive foil that is sufficiently thick to support itself and fabricated a self-supporting resistive foil with a thickness of 50 μm from a metal foil of a high-resistivity alloy. In addition, the abovementioned self-supporting foil is installed in a stress-free housing. This stress-free support technique that does not require a rigid support enables us to develop a high-stability metal-foil resistor of 100 Ω. The characterization results for the resistors of 100 Ω [3]–[5] indicated that the developed resistors perform as well as the high-quality resistors of 100 Ω that are currently available [1], [6].

For daily calibration or interlaboratory comparisons, the decade resistance values ranging from 1 Ω to 10 kΩ are the most important. Therefore, we set a research target for enhancing the resistance range of the high-stability metal-foil resistors as the next step in development. In this paper, we describe the development and evaluation of a prototype model of high-stability metal-foil resistors with a resistance of 1 kΩ.

A selection of the evaluation results during the development of the resistor of 1 kΩ has been published in [7], and this paper presents a comprehensive report on the development of the resistor and an evaluation of the drift rate, temperature coefficient, and ac characteristics (frequency dependence of the resistance and phase angle). Here, the design and fabrication process of the metal-foil standard resistors are outlined in Section II. The details of the drift-rate characterization of the resistors are described in Section III, and the characterization of the temperature dependence is reported in Section IV. Finally, the characterization of the ac properties is reported in Section V.

II. Fabrication of a Metal-Foil Resistor

On the basis of the fabrication technique for resistors of 100 Ω [3]–[5], we fabricated a high-stability metal-foil resistor of 1 kΩ. The three main steps for fabricating the high-stability metal-foil resistor of 1 kΩ are as follows.

1) The self-supporting resistive foil was photoetched from a metal foil of a high-resistivity alloy to form a meander pattern. The pattern and foil thickness were calculated in advance to produce the target resistance.

   The realization of a resistance of 1 kΩ using one resistive foil is not easy because each line of the meander pattern of the resistive foil becomes too narrow. The narrow pattern makes it difficult for the foil to support itself. To solve this problem, we adopted a meander pattern that is sufficiently wide to support itself. As a result, the target resistance of one resistive foil becomes less than 1 kΩ. In this paper, we developed two types of resistive foils; one has a nominal value of 500 Ω and

Manuscript received August 18, 2014; revised December 15, 2014; accepted January 5, 2015. Date of publication February 19, 2015; date of current version May 8, 2015. The Associate Editor coordinating the review process was Dr. Lucas Di Lillo.

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Digital Object Identifier 10.1109/TIM.2015.2398955

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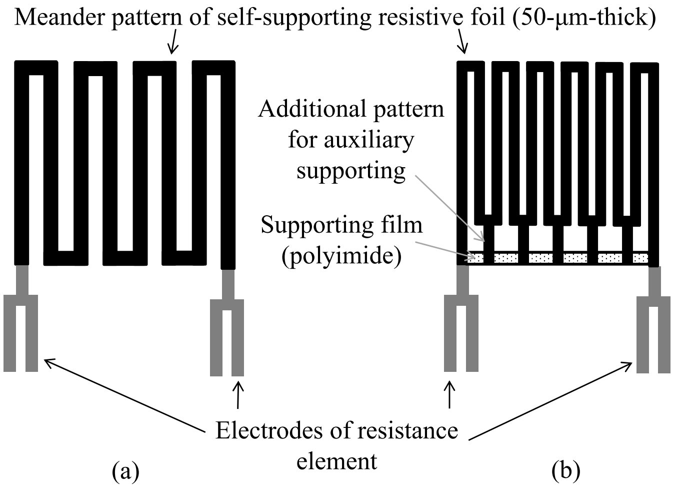

Fig. 1. Schematic of the resistive foil used for the fabrication of the metal-foil resistor. Resistive foil designs for (a) metal-foil resistor of 100 Ω that have already been developed and (b) metal-foil resistor of 1 kΩ. The nominal resistance values of the resistive foils are set to be 500 or 333 Ω. The supporting film is made of polyimide.

the other has a nominal value of 333 Ω. In addition, a supporting film made from polyimide is introduced to support the meander pattern of the resistive foil. Fig. 1 shows a schematic of the resistive foil used for the fabrication of the metal-foil resistor. Fig. 1(a) shows the resistive foil design for the metal-foil resistor of 100 Ω, which has already been developed [3]. Fig. 1(b) shows the resistive foil design for the resistive foils of 500 and 333 Ω. The supporting film and meander pattern are connected to an additional pattern of the meander pattern in Fig. 1(b).

2) After photoetching and fabrication of the supporting film, the foils were sealed in a ceramic box and filled with silicone oil. The measurement terminals were derived from the ceramic box. The ceramic box containing the foil is called the resistor device. The resistor devices of 500 and 333 Ω appear to be the same as the resistor device of 100 Ω, which is shown in Fig. 1(a) [5].
3) The metal-foil resistor of 1 kΩ was fabricated using the aforementioned resistor devices connected with a compensation resistor. The compensation resistor is added to adjust the deviation from the nominal resistance (1 kΩ) to be less than 10 $\mu\Omega/\Omega$. The resistor devices and compensation resistor were placed inside a cubic metal box. The connectors, which were connected to the resistor devices and compensation resistor, were mounted as the measurement terminals.

In this paper, two resistors of 1 kΩ with a four-terminal-pair design [8] were fabricated using the aforementioned resistor devices: serial number 1 (s/n 1) and 2 (s/n 2). The s/n 1 and s/n 2 resistors were made from two resistor devices of 500 Ω and three resistor devices of 333 Ω, respectively.

Fig. 2 shows a photograph of developed resistor (s/n 1). The dimensions are depth = 95 mm, width = 95 mm, and height = 95 mm. Four Bayonet Neill–Concelman connectors were mounted as the measurement terminals.

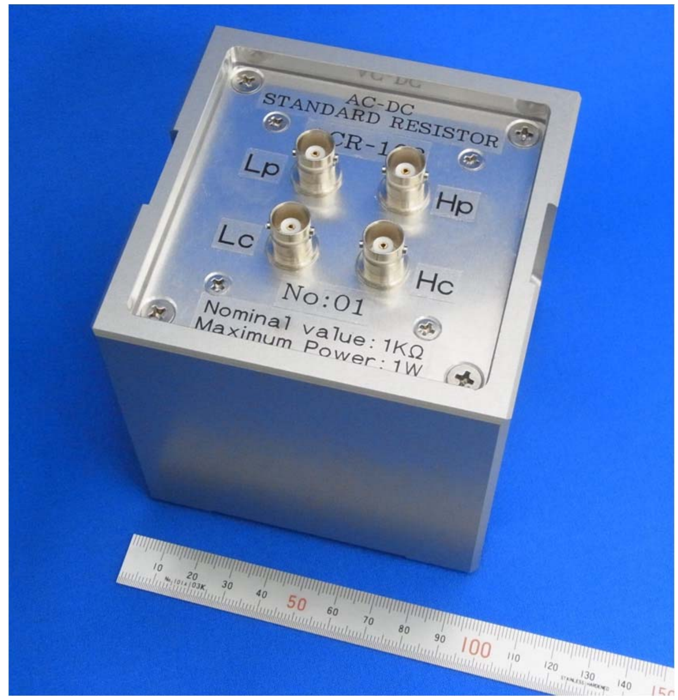

Fig. 2. Photograph of the developed metal-foil resistor of 1 kΩ (s/n 1) with a four-terminal-pair design.

III. Characterization of the Drift Rate

A. Measurement Setup

The dc resistances of the developed resistors were measured as functions of time, i.e., the drift rate. A fully automated resistance-ratio bridge based on a dc comparator (Measurement International 6010D) with a 10:1 ratio was used to measure the nominal 1-kΩ:100 Ω resistance ratio. The reference resistor of this measurement was a wire-wound resistor of 100 Ω (esi/Tegam, SR102). The SR102 resistor is periodically calibrated on the basis of the quantized Hall resistance at the NMIJ. From the continuous calibration results for more than three years, the drift rate of the SR102 resistor was revealed. The dc resistances of the metal-foil resistors of 1 kΩ were referenced to the reference value of the SR102 resistor and were calculated on the basis of the drift rate of the SR102 resistor.

During the drift-rate evaluation of the metal-foil resistors of 1 kΩ, the ambient temperature was controlled at 23 °C ± 0.01 °C using a temperature-controlled air bath. The other ambient conditions were as follows: the relative humidity was 50% ± 5% and the atmospheric pressure was 1000 hPa ± 30 hPa.

B. Measurement Results

Fig. 3 shows the resistance monitoring results of the s/n 1 and s/n 2 resistors over a period of 115 days. During this period, the resistors were deliberately subjected to drastic changes in temperature to quantitatively examine the temperature coefficient of the resistance described in Section IV. The frequency dependence and phase angle reported in Section V were measured before the start of this resistance monitoring.

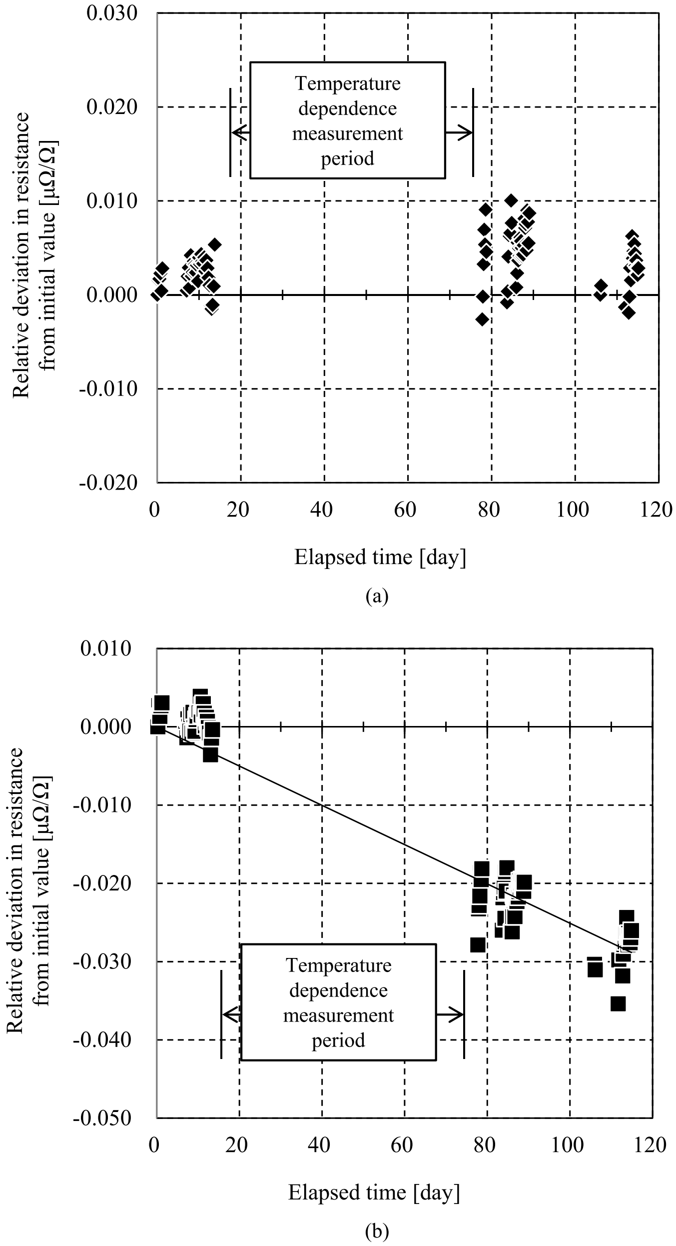

Fig. 3. DC resistance monitoring results of the metal-foil resistors of 1 kΩ over 115 days. DC resistance monitoring results of (a) s/n 1 resistor and (b) s/n 2 resistor. The solid line in (b) represents the results of the straight-line approximation.

C. Discussion

Regardless of this rigorous temperature treatment, the relative deviation in the resistance from its initial value after 115 days was found to be less than 0.010 $\mu\Omega/\Omega$ for the s/n 1 resistor [Fig. 3(a)]. In other words, the drift rate of the s/n 1 resistor is considered to be less than 0.010 $\mu\Omega/\Omega$.

As the resistance monitoring results of the s/n 2 resistor exhibited an apparent linear change, a straight-line approximation using the least-squares method was applied to the results. The solid line in Fig. 3(b) represents the approximation results. From the slope of this line, the drift rate of the s/n 2 resistor was estimated to be -0.092 ($\mu\Omega/\Omega$)/year.

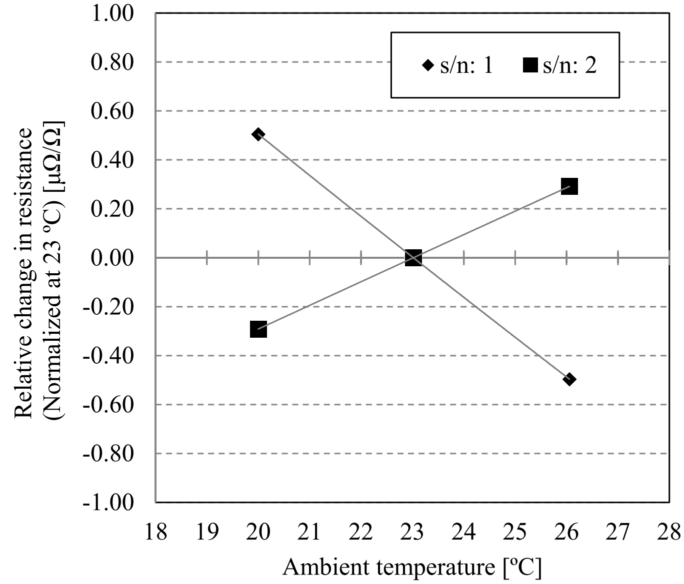

Fig. 4. Temperature dependence of the resistance (nominal value of 1 kΩ) plotted as the relative change in the resistance normalized to the value at 23 °C. The solid lines represent the second-order regression lines.

The drift rate of the previously developed metal-foil resistor of 100 Ω was evaluated to be less than 0.10 ($\mu\Omega/\Omega$)/year [3]. The s/n 1 resistor produces an excellent drift-rate result and the drift rate of the s/n 2 resistor compares favorably with the previously developed metal-foil resistor of 100 Ω. From these results, it can be concluded that the supporting films added to the metal foil do not affect the long-term monitoring results of the dc resistance.

IV. Characterization of the Temperature Dependence

A. Measurement Setup

The dc resistances of the developed resistors were measured as functions of temperature. The aforementioned 6010D resistance bridge with a 10:1 ratio was used to measure the nominal 1-kΩ:100 Ω resistance ratio. The current through the resistor of 1 kΩ was chosen to be 0.316 mA. The aforementioned SR102 resistor was used as a reference resistor for this measurement, and it was immersed in the temperature-controlled air bath. The temperature around the SR102 resistor was controlled at 22.6 °C ± 0.5 °C during this measurement. To evaluate the temperature coefficients of the metal-foil resistors, they were installed in the temperature-controlled air bath. The temperature was varied in a stepwise manner [1) 23 °C →; 2) 20 °C →; 3) 26 °C →; and 4) 23 °C].

B. Measurement Results

Fig. 4 shows the temperature dependence of the resistance of the s/n 1 and s/n 2 resistors. From the results, the second-order regression lines were calculated, represented by the solid lines in Fig. 4. The first-order temperature coefficient at 23 °C (α_{23}) and the second-order temperature coefficient (β) of each resistor were estimated from the coefficients of these lines. The results for α_{23} and β are listed in Table I.

TABLE I
TEMPERATURE COEFFICIENTS OF METAL-FOIL RESISTORS

	Temperature coefficient	
	α_{23} [(μΩ/Ω) / °C]	β [(μΩ/Ω) / °C^2]
s/n: 1	–0.165	0.002
s/n: 2	0.096	0.000

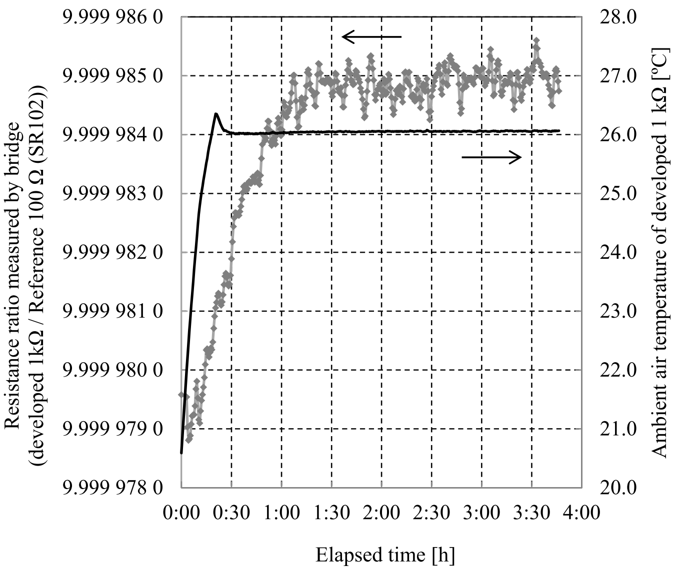

Fig. 5. Response to a temperature change for the s/n 2 resistor. The ambient temperature of the developed metal-foil resistor was changed from 20 °C to 26 °C. The left vertical axis shows the measured resistance ratio between the developed resistor of 1 kΩ and reference resistor of 100 Ω. The right vertical axis shows the ambient temperature of the s/n 2 resistor.

The ambient temperature of the s/n 1 and s/n 2 resistors was varied in stepwise manner [1) 23 °C →; 2) 20 °C →; 3) 26 °C →; and 4) 23 °C], as described in Section IV-A. To examine the hysteresis of the resistance value, the resistance value between the before-temperature-dependence measurements [measurement results in step 1) 23 °C] and the after-temperature-dependence measurements [measurement results in step 4) 23 °C] were compared. The resistance differences between the measurement results in steps 1) and 4) are calculated to be 0.016 $\mu\Omega/\Omega$ for the s/n 1 resistor and 0.009 $\mu\Omega/\Omega$ for the s/n 2 resistor. No significant differences were observed between the measurement results in steps 1) and 4).

During the temperature-dependence measurement, the resistance ratio between the developed metal-foil resistor of 1 kΩ and the reference resistor of 100 Ω was monitored as a function of time. Part of these monitoring results for the s/n 2 resistor is shown in Fig. 5. When the air-bath temperature of the s/n 2 resistor was changed from 20 °C to 26 °C, the resistance ratio distinctly and quickly followed the temperature change. The resistance was stabilized within 2 h in order for the temperature to reach equilibrium with the air-bath temperature.

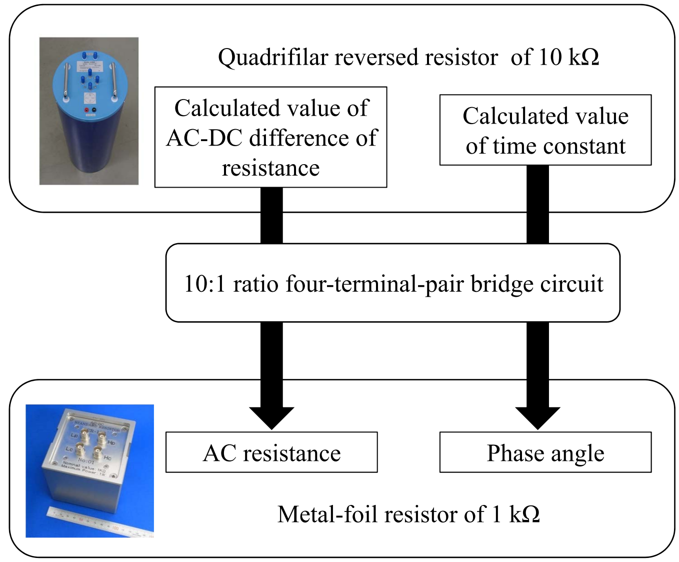

Fig. 6. Measurement procedure for the frequency dependencies of the resistance and phase angle of the developed metal-foil resistor of 1 kΩ.

C. Discussion

α_{23} of the previously developed metal-foil resistor of 100 Ω was evaluated to be less than 0.1 ($\mu\Omega/\Omega$)/°C [3]. α_{23} of the s/n 1 resistor is slightly larger than α_{23} of the previously developed metal-foil resistor of 100 Ω. However, α_{23} of the s/n 2 resistor is comparable with the previously developed metal-foil resistor of 100 Ω. From these results, it can be concluded that the supporting films added to the metal foil do not crucially affect the temperature dependence.

V. CHARACTERIZATION OF THE AC PROPERTIES

A. Measurement Setup

The resistance and phase angle of the developed metal-foil resistor or 1 kΩ was measured as a function of the frequency. The measurement procedure is shown in Fig. 6. The frequency dependence of the resistance of the resistor was measured with reference to the calculated ac–dc difference value [9] of a quadrifilar reversed resistor (nominal resistance value of 10 kΩ). The phase angle of the resistor was measured on the basis of the calculated time constant [10] of the aforementioned quadrifilar reversed resistor. A four-terminal-pair bridge circuit with a 10:1 ratio transformer [8] was used for this measurement. The frequency dependence of the 10:1 ratio of the transformer was evaluated using the inductive voltage divider calibration system of the NMIJ [11].

The measurement frequency was varied in a stepwise manner (0.398, 0.995, 1.592, and 1.989 kHz), and the applied rms voltage was 1 V in these measurements. The frequencies differ slightly from 0.4, 1, and 2 to remove the harmonic effects of the power system. During the measurements, the ambient temperature of the developed metal-foil resistor of 1 kΩ was controlled within 23.00 °C ± 0.02 °C using a temperature-controlled air bath.

B. Frequency Dependence of the Resistance

The resistance measurement results are shown in Fig. 7, which are plotted as the relative change in the resistance

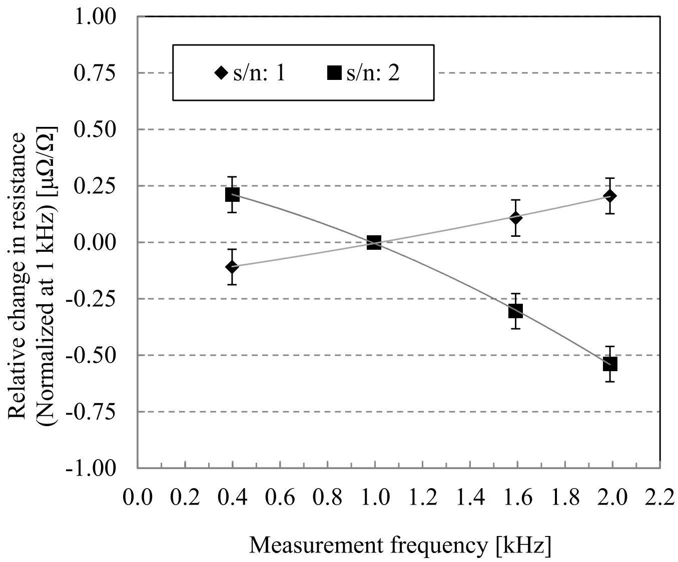

Fig. 7. Frequency dependence of the resistance (nominal value of 1 kΩ) plotted as the relative change in the resistance normalized to the value at 1 kHz. The solid lines represent the quadratic approximation curves.

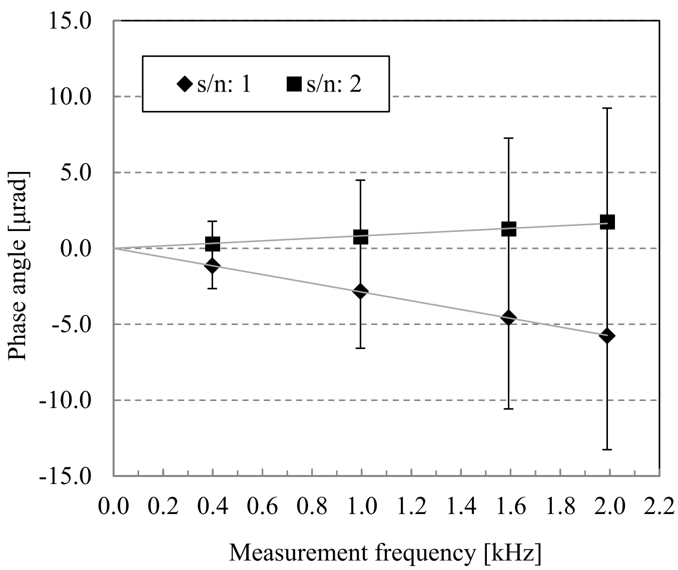

Fig. 8. Phase angles of the metal-foil resistors of 1 kΩ. The solid lines represent the results of straight-line approximations.

normalized to the values at 1 kHz (0.995 kHz). The dots represent the average values of three repeated measurements and the error bars represent the relative standard uncertainties. From the results, the quadratic approximation curves were calculated, represented by the solid lines in Fig. 7. The curve for the s/n 1 resistor has a slope of 0.14 ($\mu\Omega/\Omega$)/kHz and a curvature of 0.02 ($\mu\Omega/\Omega$)/(kHz)^2, and the curve for the s/n 2 resistor has a slope of -0.11 ($\mu\Omega/\Omega$)/kHz and a curvature of -0.21 ($\mu\Omega/\Omega$)/(kHz)^2.

C. Phase Angle

The results of the phase-angle measurements are shown in Fig. 8. The dots represent the average values of three repeated measurements and the error bars represent the standard uncertainties. As the phase-angle results exhibited a linear change, the straight-line approximations using the least squares method were applied to the results and are indicated by solid lines in Fig. 8. From the slope of these lines, the time constants were estimated to be -0.46 ns and 0.12 ns for the s/n 1 and s/n 2 resistors, respectively.

D. Discussion

For the previously developed metal-foil resistor of 100 Ω, no frequency dependence on the resistance was observed below 2 kHz within the uncertainty range of approximately 1.3 $\mu\Omega/\Omega$ (relative standard uncertainty) [5]. In this paper, the standard uncertainty of the frequency dependence measurement is estimated to be approximately 0.1 $\mu\Omega/\Omega$. Thus, the frequency dependence of the resistance is clearly recognized.

In the phase-angle results, the time constant of the s/n 2 resistor is one quarter of the time constant of the s/n 1 resistor. We consider that this difference in the time constant is caused by the difference in the patterns of the resistive foils. The capacitive coupling within the resistor-device meander pattern of the s/n 2 resistor would be plausible for the realization of a small phase angle.

VI. Conclusion

A prototype model of a metal-foil resistor with a resistance of 1 kΩ was developed in collaboration with JEMIC, Alpha Electronics Corporation, and the NMIJ. Two resistors of 1 kΩ with a four-terminal-pair design were fabricated using resistor devices that have the new resistor-device design. The s/n 1 and s/n 2 resistors were made from two resistor devices of 500 Ω and three resistor devices of 333 Ω, respectively. To realize a stable configuration of the metal foil of these resistor devices, a supporting film made from polyimide and an additional resistive-foil supporting pattern were introduced. As key characteristics of the developed resistor, the drift rate, the temperature coefficient of the resistance, the frequency dependence of the resistance, and the phase angle were evaluated. From the evaluation results, it was found that the s/n 1 and s/n 2 resistors have different characteristics. The s/n 1 resistor has a very small drift rate, and its resistance has a small frequency dependence. Further, the s/n 2 resistor has a good first-order temperature dependence and a very small phase angle in the frequency range from 400 Hz to 2 kHz.

From the drift-rate and temperature dependence evaluation results, it can be concluded that the supporting films added to the metal foil may not affect the long-term monitoring results of the dc resistance and temperature dependence.

In this paper, the dc resistance monitoring period is only 115 days. It is considered that continuous monitoring is needed to evaluate the drift rate more precisely. We also consider that an analysis of the capacitive coupling within the resistor-device meander pattern of the s/n 2 resistor is useful to realize a zero-time-constant resistor.

The resistor developed in this paper has small and predictable drift behavior as well as other superior characteristics. Utilization of a resistor of this type will enhance the reliability of an ac resistance standard and other related standards such as an ac shunt standard [12] and an inductance standard [13]. It is also expected that this type of resistor will be utilized to perform international comparisons to demonstrate the international equivalence of ac resistance measurements among the national metrology institutes.

ACKNOWLEDGMENT

The authors would like to thank Dr. Y. Sakamoto for her helpful discussion.

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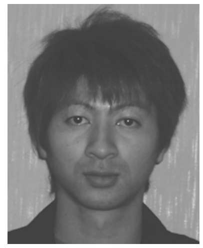

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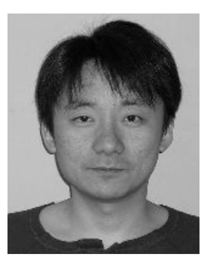

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