Magnetoresistance of RuO_2-based resistance thermometers below 0.3 K

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(Received 11 July 2000; accepted 26 March 2001)

We have determined the magnetoresistance of RuO_2-based resistors (Scientific Instruments (SI) RO-600) between 0.05 and 0.3 K in magnetic fields up to 8 T. The magnetoresistance is negative around 0.5 T and then becomes positive at larger fields. The magnitude of the negative magnetoresistance increases rapidly as the temperature is lowered, while that of the positive magnetoresistance has smaller temperature dependence. We have also examined the temperature dependence of the resistance below 50 mK in zero magnetic field. It is described in the context of variable-range-hopping (VRH) conduction down to 15 mK. Hence, the resistors can be used as thermometers down to at least 15 mK.

I. INTRODUCTION

As promising low-temperature thermometers, RuO_2-based thick-film chip resistors have been introduced (for example [1]). The advantages of such resistors are reproducibility and reasonably small magnetoresistance. In order to implement the accuracy of the thermometry in magnetic fields, a lot of works has been devoted to the magnetoresistance measurements of RuO_2-based resistors [2–11]. Unfortunately, the magnetoresistance seems to be dependent on the detail of the manufacturing process. In the case of commercial resisters, results vary even in the sign of the magnetoresistance depending upon the manufacturing company as summarized in [8, Table 1].

Recently RuO_2-based resistors produced by Scientific Instruments Inc. (SI) are used in many laboratories. However, there is no substantial publication on their magnetoresistance to the best of our knowledge. This is the motivation for our examining SI's resistors in this work. We focus on the temperature range of $T < 0.3$ K, where thermometry based on a physical quantity that is nominally independent of the magnetic fields is extremely troublesome, and hence, information on the magnetoresistance of resistance thermometers is extremely valuable. Note that the vapor pressure of ^{4}He or ^{3}He is no longer appropriate in this temperature range for the purpose. We have determined the magnetoresistance at temperatures down to 0.05 K in fields up to 8 T.

In addition to the magnetoresistance, we investigate the applicability of the resistors below 0.05 K. Concerning SI's resistors, the calibration is commercially available down to 0.05 K, while at present ^{3}He-^{4}He dilution refrigerators with base temperatures of $0.02 - 0.03$ K are installed in many laboratories. Hence it should be a matter of great interest how one can describe the temperature dependence of the resistance, or how well the calibration table is extrapolated to lower temperatures.

II. EXPERIMENT

We measured the resistance of two RuO_2-based thick-film chip resistors (SI model RO-600A, S/N 1848 and 1849) at temperatures $T < 0.3$ K using a ^{3}He-^{4}He dilution refrigerator. Magnetic fields up to $B = 8$ T were applied by means of a superconducting solenoid. The resistors are "exposed" (not canned) chips. One of them [Resister A (S/N 1848)] was placed so that the direction of the magnetic field was parallel to the film. For the other [Resistor B (S/N 1849)], the direction of the magnetic field was perpendicular to the film, and hence, perpendicular to the current flow as well. The temperature was determined by a ^{3}He-melting-curve thermometer (MCT) [12]. The MCT was placed in a region where the magnetic field was always nominally zero, i.e., magnetic fields applied for the magnetoresistance measurements were compensated in the region. Moreover, the ^{3}He melting curve is known to have a sufficiently small magnetic-field dependence in the temperature range of this work [13]. Hence, the temperature determined by the MCT is not affected by the magnetic-field applied for the magnetoresistance measurements at all.

Both the resistors and the MCT were thermally connected to the mixing chamber of the refrigerator with thick cold fingers made of pure copper or pure silver. As for the resistors, the signal leads, which also act as a heat sink, were glued to one of the cold fingers with GE7031 varnish. For the resistance measurements we employed ac methods at $f \leq 25$ Hz. The output voltage of the sample was detected by a voltage amplifier (DL Instruments 1201) and/or a lock-in amplifier (EG&G Princeton Applied Research 124A or Standford Research System SR830DSP) at $T \leq 0.09$ K. At $T \geq 0.09$ K, we used

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a resistance bridge (RV-Elekroniikka AVS-45). We have confirmed that the resistance obtained by the two methods agree with each other at $T = 0.09$ K.

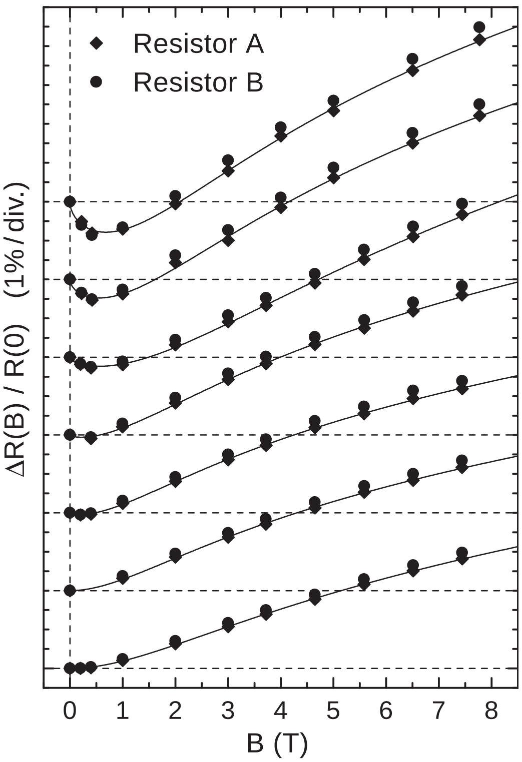

FIG. 1. Relative change of resistance as a function of magnetic field for the two RuO_2-based resistors at constant temperatures. The temperatures from top to bottom in units of K are 0.05, 0.06, 0.09, 0.12, 0.16, 0.20, 0.24, respectively. The origin of each data set is offset for clarity. The solid curves represent the fits of $\Delta R(B)/R(0) = A_1 B^{1/2}[1 + (B/B_1^*)^{-3/2}]^{-1} - A_2 B^{1/2}$ for Resistor A.

III. RESULTS AND DISCUSSION

A. Magnetoresistance

The relative change of resistance $\Delta R/R$ and of the corresponding apparent temperature $\Delta T/T$, i.e., temperature evaluated based on the $R - T$ calibration table for $B = 0$, are shown in Figures 1 and 2, respectively, as functions of applied magnetic field for Resistors A and B. The two resistors are nominally identical (Note that their serial numbers are 1848 and 1849.) and the resistance at $B = 0$ agrees within 1% at all the temperatures of the magnetoresistance measurements. Hence, the orientation dependence of the magnetoresistance can be probed by comparing the results of the two resistors. One sees in Figures 1 and 2 that the orientation dependence is much smaller than the magnitude of the magnetoresistance. This characteristic is preferable from a practical point of view because the users do not have to be worried about the orientation. In usual case where the canned chip is used, one cannot even know the orientation of the film.

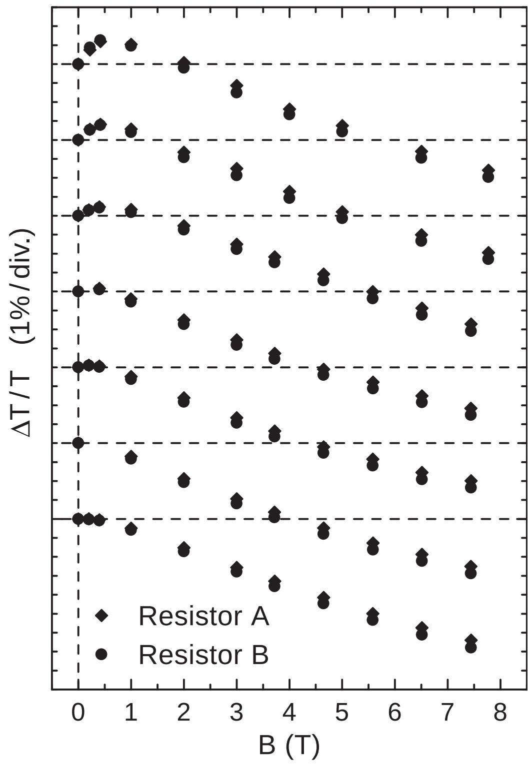

FIG. 2. Relative change of apparent temperature as a function of magnetic field at constant temperatures. The temperatures are the same as in Figure 1. The origin of each data set is offset for clarity.

TABLE I. Magnetic-field-induced relative resistance change $[R(B) - R(0)]/R(0)$ in units of % at $B = 0.5$ T.

Resistor	0.05 K	0.06 K	0.09 K	0.12 K	0.16 K
A	-1.7	-1.1	-0.6	-0.2	0.0
B	-1.8	-1.0	-0.5	-0.1	0.0

TABLE II. Magnetic-field-induced relative resistance change $[R(B) - R(0)]/R(0)$ in units of % at higher magnetic fields. The results for Resistors A and B are compared with the values in Ref. 14.

	0.08 K			0.14 K			0.28 K		
	A	B	Ref. 14	A	B	Ref. 14	A	B	Ref. 14
2 T	1.0	1.3	1.4	1.5	1.8	1.3	1.3	1.4	1
4 T	3.6	4.1	4	3.7	4.0	3.4	3.1	3.3	3
6 T	6.1	6.6	7	5.6	6.0	5.3	4.5	4.7	5
8 T	8.2	8.7	8	7.3	7.7	7	5.6	5.9	6

Now we shall look at the sign and the magnitude of the magnetoresistance. Negative magnetoresistance appears at low-field regime at $T < 0.2$ K, which is consistent with the information by SI [14] referring to the existence of an initial small negative magnetoresistance at temperatures below 0.25 K at low fields (less than about 1.5 T). The magnitude of the negative magnetoresistance, which is not described in Ref. 14, grows rapidly as the temperature is lowered, and at $T = 0.05$ K for example, $\Delta R(B)/R(0)$ at $B \approx 0.5$ T is -2%, which is no longer "small". In Table I is given $\Delta R(B)/R(0)$ at $B = 0.5$ T at several temperatures. When the RuO_2-based resistors are used as thermometers, the relatively strong temperature dependence of the magnetoresistance reduce the accuracy of the temperature measurements, and hence, an appropriate care should be taken with the negative magnetoresistance. The magnetic-field dependence at higher fields, on the other hand, is simple. In Table II, we summarize the magnetoresistance ratio of Resistors A and B determined by the experiment at high fields. The values given in the specifications [14] are also shown in the table. We find the magnetoresistance at high fields are described well by the values in the specifications.

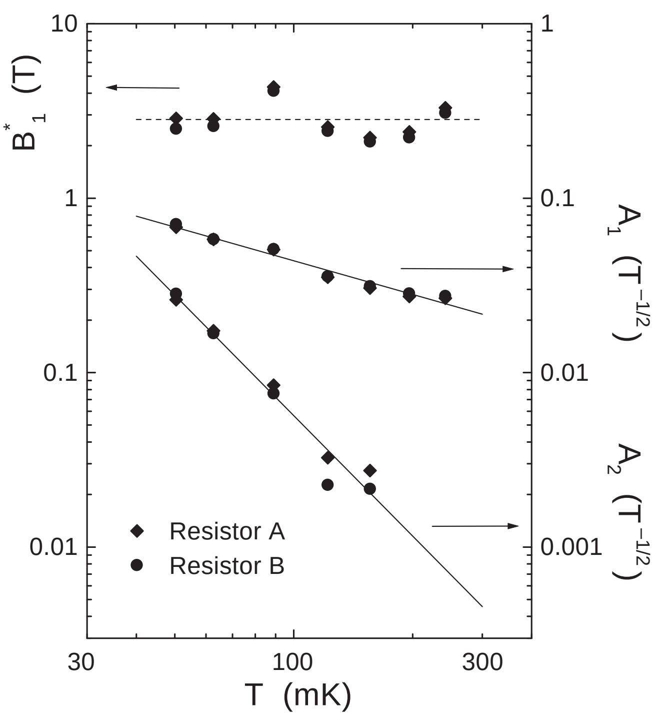

FIG. 3. Parameters A_1, A_2, and B_1^* obtained by fitting $r = r_1 + r_2'$ [See Equations (1), (3), and (5).] vs. temperature. The horizontal dotted line represents the average of B_2^*, and the solid lines the best power-law fits for A_1 and A_2.

As an empirical expression for

$$r \equiv [R(B) - R(0)]/R(0) \tag{1}$$

of the SI resistors at $0.05\text{ K} \le T < 0.3$ K, we propose

$$r_{ap}(B,T) \equiv 0.838\, T^{-0.641}\, B^{1/2} \left[1 + \left(\frac{B}{2.83}\right)^{-3/2}\right]^{-1} - 220\, T^{-2.29}\, B^{1/2}, \tag{2}$$

where B and T are in units of T and mK, respectively. The underlying idea is as follows. Goodrich *et al.* measured the magnetoresistance up to 18 T or 32 T and reported $B^{1/2}$ dependence at $B > 2.5 - 3$ T [11]. In sufficiently low magnetic fields, on the other hand, magnetoresistance should show B^2 dependence irrespective of its origin so long as the symmetric relation $r(-B) = r(B)$ holds. Based on these points, we introduce

$$r_1(B) \equiv A_1 B^{1/2} \left[1 + \left(\frac{B}{B_1^*}\right)^{-3/2}\right]^{-1}, \tag{3}$$

where $A_1 > 0$ is a coefficient and B_1^* is the magnetic field characterizing the crossover of the field dependence. Note that $r_1 \approx (A_1 B_1^{*\,-3/2})B^2$ for $0 < B/B_1^* \ll 1$ and $r_1 \approx A_1 B^{1/2}$ for $B/B_1^* \gg 1$. We fit $r = r_1$ to the data in Figure 1 at $T = 0.20$ K and 0.24 K, where only positive magnetoresistance is seen within the resolution of our measurements. The results for Resistor A is shown in the same figure. In order to express the negative magnetoresistance which is clearly seen at lower temperatures, we add

$$r_2(B) \equiv -A_2 B^{1/2} \left[1 + \left(\frac{B}{B_2^*}\right)^{-3/2}\right]^{-1}, \tag{4}$$

where $0 < A_2 < A_1$ and $0 < B_2^* < B_1^*$. In our resisters $B_2^* \ll 0.1$ T is found, and hence

$$r_2 \approx r_2' \equiv -A_2 B^{1/2} \tag{5}$$

is a good approximation at $B \geq 0.1$ T. The curves in Figure 1 for Resistor A at $T \leq 0.16$ K are the fits of $r = r_1 + r_2'$. The fits yield the values shown in Figure 3. The temperature dependences of A_1 and A_2 are described by the power law. This is the background of Equation (2). We have neglected the temperature variation of B_1^* and used the average value 2.83 T. The deviation from r_{ap} is shown in Figure 4. The data from Ref. 14 are also plotted. All the data points at $B \leq 8$ T are reproduced by Equation (2) within the error of 0.015.

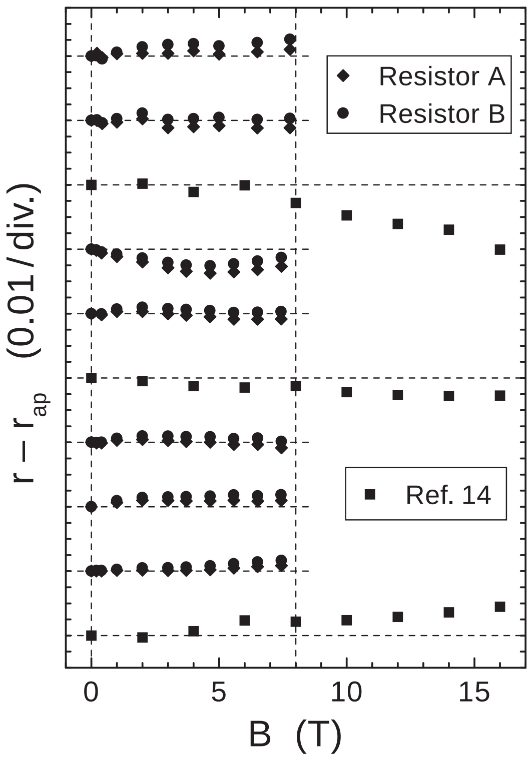

FIG. 4. Deviation of the relative resistance change $r \equiv [R(B) - R(0)]/R(0)$ from r_{ap} given by Equation (2). The temperatures from top to bottom in units of K are 0.05, 0.06, 0.08, 0.09, 0.12, 0.14, 0.16, 0.20, 0.24, 0.28, respectively. The origin of each data set is offset for clarity.

B. Temperature dependence in zero magnetic field

In Figure 5 the resistance in zero magnetic field is plotted as a function of $T^{-1/4}$ in a semi-log scale. We find the temperature variation of the resistance for Resistor B at the lowest temperature range is described by

$$R(T) \propto \exp[(T_0/T)^p]. \tag{6}$$

with $p = 1/4$. The temperature dependence of the resistance of RuO_2-based resistors at low temperatures has been analyzed in terms of variable-range hopping (VRH) conduction [3,5,7,8,10,15]. In some works [7,8,15], the exponent p was treated as a fitting parameter and various values ($0.14 \leq p < 0.71$) were reported. According to the theory of VRH [16], p is determined by the dimensionality d and the shape of the density of states around the Fermi level. For $d = 3$ and the single-particle density of states $g(E)$ expressed by

$$g(E) \propto |E - E_F|^n, \tag{7}$$

where E_F is the Fermi energy, the exponent p is given by

$$p = \frac{n+1}{n+4}\,. \tag{8}$$

For *thick*-film chip resistors $d = 3$ is reasonable, and the very small orientation dependence of the magnetoresistance that we saw in the preceding subsection is consistent with this idea. The present result, $p = 1/4$, supports the constant density of states, $n = 0$, around the Fermi level rather than the Coulomb pseudo gap, $n = 2$. Good fits with $p = 1/4$ have also been reported for the resistors manufactured both by ALPS [3] and by Dale (RCWP575 [5], RC550 [10]).

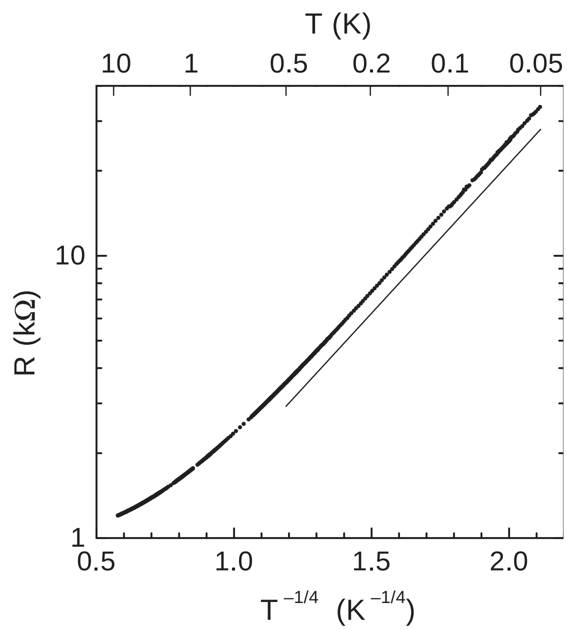

FIG. 5. Resistance in zero magnetic field as a function of $T^{-1/4}$ for Resistor B. The line represents the best fit using the data between 0.05 K and 0.5 K. The fit is shifted downward for easier comparison.

C. Applicability below 0.05 K

At very low temperatures, resistors are easily overheated, i.e., the measured temperature can be considerably higher than the real temperature. An obvious source of the overheating is the Joule heat $P = RI^2$ by the bias current I for the resistance measurements. Besides P, however, there can be other sources of overheating, such as the energy dissipation due to the high-frequency noise, due to the induced current by a ground loop, due to the thermoelectric power, and so on. Heat conduction through the electrical leads can be other source of heat input in case of improper thermal anchoring. Because of these, it is not an easy task to ensure the absence of overheating in experiments. Fortunately, in the present case, we can determine whether overheating is present or not, because the temperature dependence of the resistance given by Equation (6) with $p = 1/4$ is reasonably expected to hold even at temperatures lower than 0.05 K.

In order to estimate how small the heat flow into the resistors should be, we measured the resistance at various bias currents in zero magnetic field. In Figure 6 we show P vs. the temperature of the resistor T_r determined from its resistance. During the measurements, the temperature of the mixing chamber T_m was always lower than 6 mK. All the data points align on straight lines, i.e.,

$$\dot{Q} \approx A T_r^q \tag{9}$$

holds, where $\dot{Q}$ is the heat input to the resistor, which must be dominated by P when $T_r \gg T_m$ as in Figure 6, and A is a coefficient. The dashed lines in Figure 6 represent fits of Equation (9). We obtain $q = 3.5 \pm 0.1$ and $\log_{10} A = -5.9 \pm 0.02$ for Resistor A, and $q = 3.4 \pm 0.1$ and $\log_{10} A = -6.0 \pm 0.03$ for Resistor B, where A is in units of W/K^q.

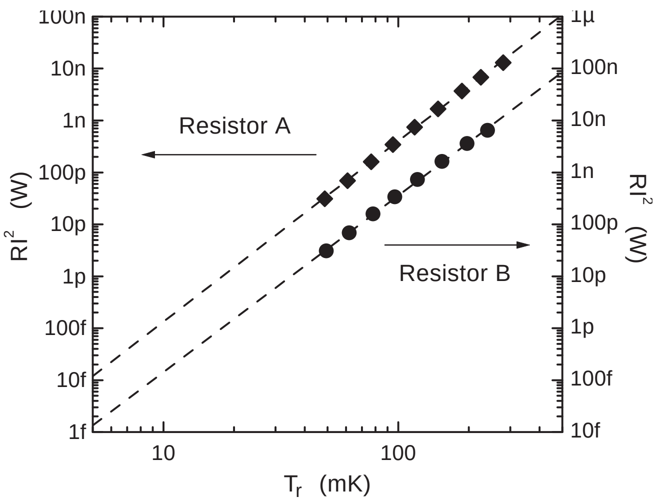

FIG. 6. Measuring power vs. the temperature of the resistor determined from its resistance. During the measurements, the temperature of the mixing chamber was lower than 6 mK.

Although the lowest temperature in Figure 6, $T_r = 49$ mK, is much higher than T_m, we expect that the dependence of Equation (9) holds even for much smaller heat input. In this case, we should modify the equation as

$$\dot{Q} = A(T_r^q - T_m^q) \tag{10}$$

because T_r should be equal to T_m when $\dot{Q} = 0$. We should note that this relationship is expected when there is a distinct bottleneck in the path of heat flow from electron system in the sensor to the refrigerator. Possible sources of such bottleneck are poor electron-phonon coupling in the RuO_2, the Kapitza resistance, and the thermal resistance of electrically insulating material. Unfortunately, we cannot identify which is the case at present. If Equation (10) holds for arbitrary T_m and T_r, it means that the thermal impedance

$$Z = \lim_{\dot{Q} \to 0} \frac{\Delta T}{\dot{Q}} \tag{11}$$

between the electron system and the refrigerator is proportional to T^{-q+1}, where $\Delta T \equiv T_r - T_m$. Such power-law dependence of Z on T has been reported for RuO_2-based resistors [7].

Using an approximation of Equation (10) in the limit of $\Delta T \ll T_m$,

$$\dot{Q} \approx Aq(\Delta T / T_r) T_r^q, \tag{12}$$

we can evaluate the maximum value allowed for $\dot{Q}$, which is simultaneously the upper bound for P, for a given accuracy in temperature determination, $\Delta T / T_r$. For example, in order to achieve $\Delta T / T_r < 0.01$, $P < 0.2$ pW is required at 30 mK and $P < 5$ fW at 10 mK. Keeping P sufficiently low, we measured the resistance down to 6 mK as shown in Figure 7. For $T > 15$ mK the resistance is described well by Equation (6) with $p = 1/4$, and hence the resistors are applicable. The temperature dependence of resistance levels off below 15 mK in spite of small excitation current. This leveling-off is explained if we assume the excess heat input to the resistor of about 0.1 pW.

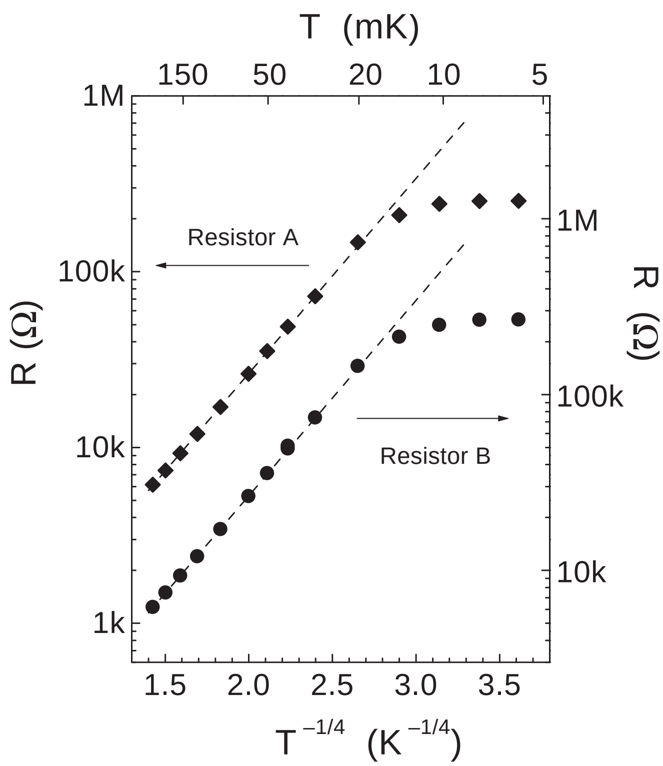

FIG. 7. Resistance as a function of $T^{-1/4}$ for both the resistors.

IV. CONCLUSION

We have determined the magnetoresistance of RuO_2-based resistors produced by Scientific Instruments Inc. between 0.05 K and 0.3 K in magnetic fields up to 8 T.

Negative magnetoresistance is observed around 0.5 T, and its magnitude grows rapidly as the temperature is lowered. Positive magnetoresistance at high magnetic fields has smaller temperature dependence, and its magnitude is consistent with the information provided by the company. We have also investigated the characteristics of the resistors below 50 mK in zero magnetic field. The resistors are applicable down to at least 15 mK.

ACKNOWLEDGEMENTS

The measurements were carried out at the Cryogenic Center, University of Tsukuba, Japan. M. W. would like to thank Japan Society for the Promotion of Science (JSPS) for financial support.

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