Cryogenics 35 (1995) 525–528

0011-2275/95/$10.00

Magnetoresistance of thick-film chip resistors at millikelvin temperatures

K. Uhlig

Walther-Meissner-Institut für Tieftemperaturforschung der Bayerischen Akademie der Wissenschaften, Walther-Meissner Strasse 8, D-85748 Garching b. München, Germany

Received 20 February 1995

Data are presented for the magnetoresistance of two types of commercial thick-film chip resistors in the millikelvin temperature regime (1 kΩ Dale RCW-575 and 2.7 kΩ Philips RC-01). Chip resistors, which are intended for use in microcircuit electronics, have become an important tool in low temperature research due to their applicability as reliable secondary thermometers. They have good reproducibility and fast thermal response, are small and are easy to mount. The temperature range covered in this work is between 1 K and 25 mK, and the magnetic field range is from 0 to 7 T. For both resistors, the magnetoresistance (MR) is negative for low magnetic fields, and positive for high fields. The transition point from negative to positive MR and the magnitude of the MR are strongly temperature dependent. At 25 mK and 7 T, which are the lowest temperature and the highest field measured, the MR value is a few per cent. On average, the MR of the Philips resistor is ≈50% lower than that of the Dale resistor.

Keywords: low temperature thermometers; thick-film chip resistors; magnetoresistance

Thick-film resistors have gained increasing importance in low temperature physics as low temperature sensors in recent years[1–6]. One reason is that the carbon composition resistors[7–10] which had been widely used for secondary thermometry, namely the Speer and Matsushita carbon compound resistors, are no longer manufactured. A second reason is that thick-film thermometers are much easier to prepare than carbon thermometers: it takes considerable time and experience to make a low temperature thermometer from a resistor[11]. Thirdly, the reproducibility of the temperature calibration of chip resistors is generally better than that of carbon thermometers. For instance, for the chip sensors reported in this article, the reproducibility of the resistance at 4.2 K between different cool-downs was always better than 0.1%. Lastly, the magnetoresistance of chip resistors is small, and so the corrections are small when they are used for thermometry in magnetic fields.

Thick-film resistors are considerably cheaper than germanium thermometers[12], and are also much easier to mount; in addition, germanium resistors which can be used reliably below 50 mK are hard to come by. Their magnetoresistance is large.

Experimental details

The resistance thermometers investigated in this work were chip resistors of the type Dale RCW-575 (Dale Electronics, Norfolk, NB, USA) with a room temperature resistance of 1 kΩ, and Philips RC-01 (NV Philips, Eindhoven, The Netherlands) with a room temperature value of 2.7 kΩ. The structure of these resistors has been described elsewhere[1–6]. Standard self-balancing resistance bridges (VS3 and VS4, Instruments for Technology, Finland) were used to measure the resistance of the chip resistors. Low-pass filters were installed in the sensor leads to prevent RF noise from heating the sensors[7,11].

The low temperature part of the electrical leads was made from superconducting NbTi wires with a CuNi coating; they were soldered to the resistors with indium. The resistors themselves were epoxied to a silver sample holder with Stycast 1266 so that the active layer of the resistor was facing the sample holder for good thermal contact; a thin piece of cigarette paper (20 μm) was positioned between the resistor and the sample holder for electrical insulation. The sample holder was situated in the centre of a superconducting magnet, and thermally anchored to a silver platform via a bundle of 10 silver wires of 1 mm diameter each (see inset of *Figure 1*). The platform was in thermal contact with the mixing chamber of a dilution refrigerator.

One end of the magnet was field-compensated; the platform with thermometers measuring the temperature dependence of the resistors was located in this region. We used a ^3He melting curve thermometer[13] and a NBS supercon-

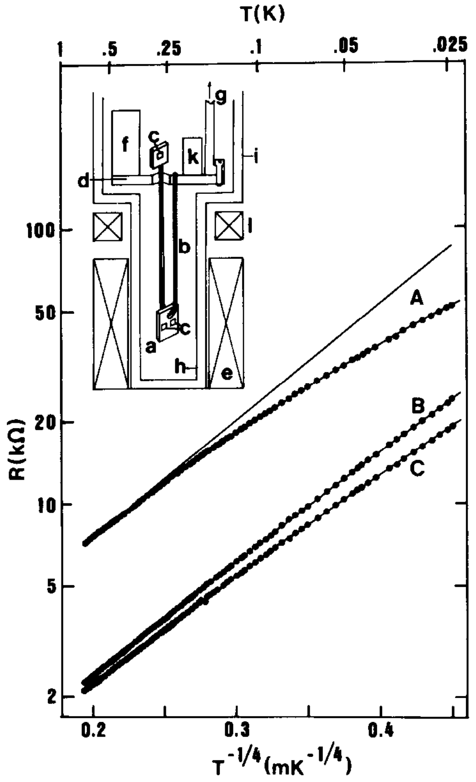

Figure 1 Resistance R (logarithmic scale) *versus* $T^{-1/4}$ for 2.7 kΩ Philips RC-01 (A), 1 kΩ Dale RCWP-575 (B) and 1 kΩ Dale RCW-575 (C). The lines through the measuring points represent fits using Equation (1) (see text for details). The straight line for resistor A is a tangent to the fit function and demonstrates deviations from a $T^{-1/4}$ dependence. Inset: low temperature part of the cryostat; a, sample holder; b, silver wire bundles; c, chip resistors; d, silver platform; e, superconducting magnet; f, NBS fixed-point device; g, thermal link to mixing chamber; h, radiation shield; i, vacuum can; k, ^3He melting curve thermometer; l, magnetic field compensation

ducting fixed point device[14] for accurate thermometry. In addition, a carbon resistor[11] and another chip resistor (1 kΩ Dale RCWP-575)[3,6] were affixed to the platform. The joints between the sample holder, the silver wires and the platform were argon welded. A second smaller bundle of silver wires ran from the sample holder to the field-compensated region, and at the end of this bundle another chip resistor was attached. This thermometer could be monitored to detect possible temperature gradients along the silver bundle while the magnetic field was on, whereas the melting curve thermometer and the resistors at the platform were needed for temperature measurement and regulation. No temperature gradients were observed between the platform and the sample holder, and so one can be confident that the resistors located at the sample holder in the magnetic field were always in good thermal contact with the platform.

Results

In *Figure 1* the logarithm of the resistance of three different thermometers is depicted as a function of $T^{-1/4}$. This kind of graph is frequently used to show the temperature dependence of the electronic conduction mechanism of the resistors due to variable-range hopping in three-dimensional localized states[15]. In *Figure 1* data of the 2.7 kΩ Philips RC-01 and of the 1 kΩ Dale RCW-575 are shown; in both cases there are systematic deviations from $T^{-1/4}$ behaviour. The data of the 2.7 kΩ RC-01 resistor can be compared with data of reference 2; here, too, the resistance of a 2.7 kΩ RC-01 resistor deviates from $T^{-1/4}$-behaviour, in agreement with present data.

For comparison data for a 1 kΩ Dale RCWP-575 resistor (see also references 3 and 6) are included in the graph. These data, too, follow a $T^{-1/4}$ law only approximately. For certain germanium resistors and carbon compound resistors $T^{-1/2}$ behaviour has been found before[16], but intermediate values of the temperature exponent have also been reported[10]. A temperature exponent of (−1/2) can be theoretically interpreted by a Coulomb interaction which leads to a gap in the density of states at the Fermi level; and a temperature exponent of (−1/3) was explained by a variable range hopping theory for two-dimensional localized states.

For thermometry purposes, the temperature dependence of the resistance of the chip resistors is better expressed by an empirical fit function of the form

$$R = \exp\left[\sum_{n=0}^{N} A_n (\ln T)^n\right] \tag{1}$$

Choosing $N = 2$ was sufficient to fit the resistance data of the Dale and Philips chip resistors for temperatures from 1 K down to 25 mK to better than 0.3%.

For $N = 2$, a semilogarithmic plot of the sensitivity

$$S = -\frac{d(\ln R)}{d(\ln T)} = -A_1 - 2A_2 (\ln T) \tag{2}$$

of the chip resistors investigated has to yield straight lines, as demonstrated in *Figure 2*. For this graph

$$S = -\frac{d(\ln R)}{d(\ln T)} = -\frac{T dR}{R dT} \tag{3}$$

was calculated by multiplying the experimental values of

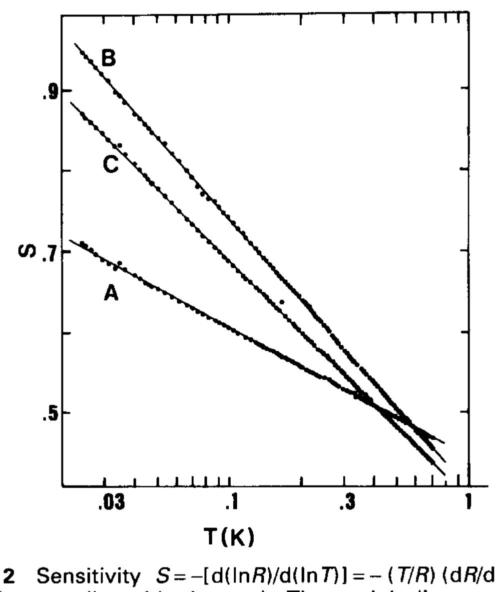

Figure 2 Sensitivity $S = -[d(\ln R)/d(\ln T)] = -(T/R)(dR/dT)$ *versus* T in a semilogarithmic graph. The straight lines are calculated using Equation (2) and points are from the experiment (see text for details). (A) 2.7 kΩ Philips RC-01; (B) 1 kΩ Dale RCWP-575; (C) 1 kΩ Dale RCW-575

Table 1 Values for fitting parameters using Equations (1) and (5) for 2.7 kΩ Philips RC-01, 1 kΩ Dale RCW-575 and 1 kΩ Dale RCWP-575 chip resistors

	RC-01	RCW-575	RCWP-575
A_0	13.49	13.31	13.874
A_1	−0.931	−1.286	−1.420
A_2	0.0351	0.0648	0.0735
B_0	−10.40	−8.864	−7.916
B_1	3.079	2.605	2.238
B_2	−0.323	−0.252	−0.203
B_3	0.0137	0.0106	0.0083

T/R with dR/dT which is the derivative of the fit function (1)

$$\frac{dR}{dT} = T^{-1}\,(A_1 + 2A_2 \ln T)\exp\left[\sum_{n=0}^{N} A_n\,(\ln T)^n\right] \tag{4}$$

The present results for the sensitivity S are not in agreement with the measurements of reference 3, where a 1 kΩ Dale RCWP-575 is described.

Alternatively, a fit function of the form[19]

$$T^{-1/4} = \sum_{i=0}^{I} B_i\,(\ln R)^i \tag{5}$$

works well for the chip resistors described, and this fit is quite useful for thermometry purposes. Taking $I = 3$ is sufficient for our temperature range between 25 mK and 1 K to give a mean square deviation of less than 1%. In *Table 1* fitting parameters A_i and B_i are depicted using Equations (1) and (5) for the 2.7 kΩ Philips RC-01, the 1 kΩ Dale RCW-575 and the 1 kΩ Dale RCWP-575 chip resistors.

Figure 3 shows the relative change in resistance of a 1 kΩ Dale RCW-575 resistor as a function of the applied magnetic field for seven different temperatures from 4.2 K to 25 mK; the various curves are offset from each other for clarity. The most conspicuous feature of the magnetic field induced resistance change is the appearance of a wide minimum in the resistance with increasing magnetic field. The effect becomes more predominant as the temperature is lowered, but even at the highest temperature of 4.2 K the minimum can still be observed. At 25 mK the magnetoresistance is negative up to 3 T, before it becomes positive. Its value in the minimum near 0.7 T is −3.5%.

In *Figure 4* the magnetic field induced relative resistance change of the 2.7 kΩ Philips RC-01 is depicted. In a magnetic field this chip resistor reveals similar features to the Dale resistor described earlier; namely, negative magnetoresistance at low fields and positive magnetoresistance at high fields. Compared with the 1 kΩ Dale resistor, the magnetoresistance is smaller on average by ≈50%.

The present results are different from the ones of reference 2 where a negative magnetoresistance has been reported for a 1.8 kΩ RC-01 chip resistor for $0.023\ \mathrm{K} < T < 0.3\ \mathrm{K}$ and $0 < H < 5\ \mathrm{T}$. This discrepancy is probably not due to an experimental problem, but more likely to different materials used by the manufacturer. On the other hand, the magnetoresistance measurements presented here are in qualitative agreement with experiments on Matsushita carbon compound resistors[17]; the magnetoresistance data of Oda *et al.* are negative, too, at low fields and becomes positive at high fields.

The dependence of the magnetoresistance on the field orientation was not studied in the present experiments. In reference 4, Willekers *et al.* report that no field orientation effects on the magnetoresistance could be observed.

At a temperature of ≈25 mK, varying the excitation voltage of the resistance bridge with the chip resistors showed that a measuring power of 10^{-13} W caused heating effects

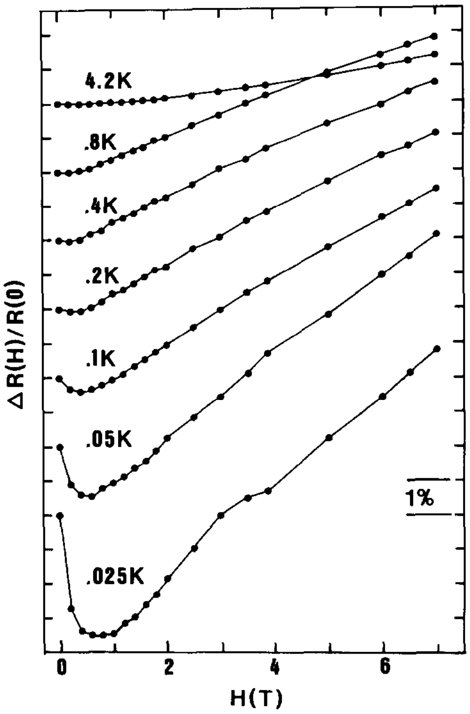

Figure 3 Magnetic field induced relative resistance change $[R(H,T) - R(0,T)]/R(0,T)$ *versus* magnetic field for the 1 kΩ Dale RCW-575 resistor for seven different temperatures. The curves for each temperature are offset for clarity

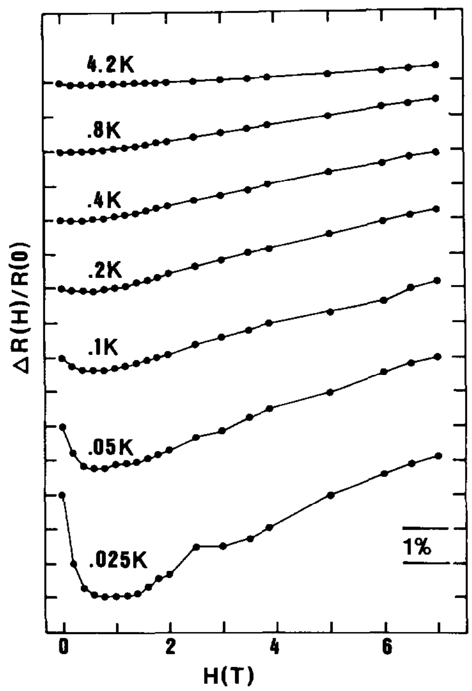

Figure 4 Magnetic field induced relative resistance change $[R(H,T) - R(0,T)]/R(0,T)$ *versus* magnetic field for 2.7 kΩ Philips RC-01 resistor for seven different temperatures. The curves for different temperatures are offset for clarity

in the sensors; heating effects became more obvious and troublesome at lower temperatures and so reliable data could not be taken below 25 mK. Possibly, the measuring range might be extended to lower temperatures by reducing the thermal resistance between the sample holder and the chip resistors.

Although heat capacity measurements of thick film resistors have been reported[5,18] it would be especially desirable to have more heat capacity and thermal relaxation time data in magnetic fields. And, above all, it would be very important to have a theoretical description of the electronic conduction mechanism in thick-film resistors which also describes the magnetoresistance.

Hopefully the results presented in this paper are useful for low temperature experimentalists for thermometry in magnetic fields and will, at the same time, stimulate more theoretical work.

Acknowledgements

The author thanks K. Neumaier and C. Probst for their interest and loan of equipment for the experiments. R. Rosenbaum's and B.S. Chandrasekhar's comments were important and helpful.

References

1 **Doi, H., Narahara, Y., Oda, Y. and Nagano, H.** *Proc LT-17* North-Holland Physics Publishing, Amsterdam, The Netherlands (1984) 405

2 **Bosch, W.A., Mathu, F., Meijer, H.C. and Willekers, R.W.** *Cryogenics* (1986) **26** 3

3 **Li, Q., Watson, C.H., Goodrich, R.G., Haase, D.G. and Lukefahr, H.** *Cryogenics* (1986) **26** 467

4 **Willekers, R.W., Mathu, F., Meijer, H.C. and Postma, H.** *Cryogenics* (1990) **30** 351

5 **Meiserl, M.W., Stewart, G.R. and Adams, E.D.** *Cryogenics* (1989) **29** 1168

6 **Briggs, A.** *Cryogenics* (1991) **31** 932

7 **Anderson, A.C.** in *Temperature: Its Measurements and Control in Science and Industry* (Ed Plumb, H.H.) Instrument Society of America, Pittsburgh, USA (1972) 773

8 **Anderson, A.C., Anderson, J.H. and M.P. Zaitlin** *Rev Sci Instrum* (1976) **47** 407

9 **Koike, Y., Fukase, T., Morita, S., Okamura, M. and Mikoshiba, N.** *Cryogenics* (1985) **25** 499

10 **Sullivan, N.S. and Edwards, C.M.** *Cryogenics* (1986) **26** 211

11 **Neumaier, K.** *Rev Phys Appl* (1984) **19** 677

12 **Zabrodskii, A.G. and Zinoveva, K.N.** *Sov Phys JETP* (1984) **59** 425

13 **Fogle, W.E., Colwell, J.H. and Soulen, R.J.** *Physica B* (1990) **165/166** 33 (and **Fogle, W.E.** personal communication)

14 **Colwell, J.H., Fogle, W.E. and Soulen, R.J.** *Proc LT-17* North-Holland Physics Publishing, Amsterdam, The Netherlands (1984) 395

15 **Mott, N.F. and Davis, E.A.** *Electronic Processes in Non-Crystalline Materials* Clarendon Press, Oxford, UK (1979)

16 **Schoepe, W., Uhlig, K. and Neumaier, K.** *Cryogenics* (1989) **29** 467

17 **Oda, Y., Fujii, G. and Nagano, H.** *Cryogenics* (1974) **14** 84

18 **Volokitin, Y.E., Thiel, R.C. and de Jongh, L.J.** *Cryogenics* (1994) **34** 771

19 **Greywall, D.A.** *Phys Rev B* (1981) **23** 2152