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Temperature and magnetic field dependence of thick-film resistor thermometers (Dale type RC550)

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We have measured the resistance of commercial thick-film chip resistors (Dale Type RC550, nominal resistance $R = 500\ \Omega$) as a function of temperature ($8\ \mathrm{mK} \leq T \leq 10\ \mathrm{K}$) and magnetic field $B \leq 7\ \mathrm{T}$ (for $T \geq 0.3\ \mathrm{K}$) at different orientations between input current, main area and magnetic field. At $30\ \mathrm{mK} \leq T < 10\ \mathrm{K}$ the temperature dependence of the resistance follows $R = A \exp(B/T^{1/4})$ in agreement with published data for a 1 kΩ thick-film chip resistance. In contrast to previously published studies of similar resistors we measured a resistance that increases approximately linearly with field at $T < 1$ K and quadratically at higher temperatures. The sensitivity to magnetic fields decreases from $(0.8 \pm 0.1)\%\ \mathrm{T}^{-1}$ at 0.3 K to $0.1\%\ \mathrm{T}^{-1}$ above 2 K for $B = 1$ T.

Keywords: thermometry; thick-film resistors; magnetoresistivity

Several groups have reported the advantages of thick-film RuO_2-based chips as thermometers for low-temperature measurements[1-5], as well as the limitations on their design[6]. Small mass (2.6 mg for the RC550 studied in this work) and size, a reasonable temperature sensitivity below 10 K, good stability, relatively low magnetoresistance make them an interesting option for low-temperature measurements in spite of anomalies observed in the low-temperature specific heat[7]. However, there are qualitative and quantitative differences in the temperature dependence and magnetoresistive behaviour of these resistors. Schoepe reported a negative magnetoresistance for 10 kΩ (nominal value) resistors[5], smaller than the one measured by Bosch *et al.*[2] (resistances between 200 Ω and 5 kΩ), and an $\exp(T_0/T^{1/2})$ temperature dependence. Meisel *et al.*[4], however, reported a positive magnetoresistance for a 1 kΩ resistor about four times larger than the one measured by Doi *et al.*[1]. Li *et al.*[3] observed positive and negative magnetoresistance of a 1 kΩ resistor depending on temperature and a $\exp(T_0/T^{1/4})$ dependence. It is also unclear in the published literature how reproducible are the measured dependencies for different samples. Possible dependence of the resistivity on the orientation between magnetic field and applied current or main surface has not yet been reported.

The aim of this work was the study of the temperature, magnetic field and any possible orientation dependence as well as the reproducibility of different thick-film resistors taken from the same batch.

Sample characteristics and experimental details

The thick-film resistors were manufactured by Dale Electronics of Nebraska and are of the type RC550 with a nominal room temperature resistance of 500 Ω. The units have the following nominal geometry; length and width 1.27 mm, 0.25 mm thickness and approximately 2.6 mg weight. The resistors have pre-tinned electrodes at the ends of one of the surfaces.

For measurements between 0.04 K and 20 K and as a function of magnetic field, three of the resistors were glued with GE 7031-varnish onto an annealed Cu-plate which was attached to the mixing chamber of a dilution refrigerator. Electrical contacts to the resistors were made by soldering Cu wires to the resistors. *Figure 1* shows the orien-

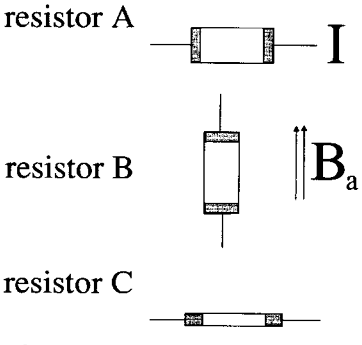

Figure 1 Experimental arrangement for the resistors A, B, and C. B_a denotes the applied magnetic field and *I* the applied current

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tations with respect to the applied magnetic field of the three resistors, which were measured 'simultaneously' with the same resistance bridge at the same input voltage and current. A fourth resistor was attached to the mixing chamber of a second dilution refrigerator. This resistor was measured below 0.1 K in zero applied magnetic field.

Above 0.04 K the resistance of the samples was measured with a 4-point resistance bridge manufactured at the Institute of Low Temperature Physics in Prag. This bridge uses a constant 60 μV, 16 Hz output voltage with 3.5 digits sensitivity in the range 20 Ω to 20 kΩ. Below 0.04 K we have used an AVS-47 resistance bridge. The dissipation in the thick-film resistors was estimated to be less than 10^{-11} W in the whole temperature range.

The field dependence of the RuO_2 resistors was measured while increasing (or decreasing) the field using a 0.4 mT s^{-1} sweep rate. The temperature was measured with two thermometers: a commercial Ge- and a carbon (Speer)- thermometer. Both were fixed in a place where the magnetic field of the superconducting solenoid was compensated for (i.e. less than 0.01 T at 7 T magnetic field in the sample).

Temperature dependence

Figure 2 shows the temperature dependence of the three resistors A, B and C in zero applied field between ~ 40 mK and 1 K. Although the resistors were from the same batch and were identically thermally attached, they showed different temperature dependencies. Although the difference between the resistances measured below 90 mK might be partially due to self-heating effects, this cannot be the reason for the small deviations observed above 0.2 K. Meisel *et al.*[4] reported deviations as much as 30% at 35 mK for the resistance of different units from the same batch, which is comparable to what we have measured. We also observed similar deviations in the temperature dependence of the resistors in a field of 7 T.

Figure 3 shows the temperature dependence of the resistor A without applied field (the Earth's field was not compensated for). In the figure we also show data from a fourth resistor measured below 100 mK. The differences between both resistors are within the width of the symbols in the logarithmic scale of the figure. The temperature dependence is similar to that reported by Meisel *et al.*[4] for 500 Ω resistors (solid line in *Figure 3*) but our resistors show ~ 7% smaller resistance at 100 mK.

The saturation of the resistance below 20 mK might be due to self-heating effects even though the measuring current was reduced to ~ 3 nA. The reproducibility of the resistors upon cycling between room temperature and low temperature was within 1%.

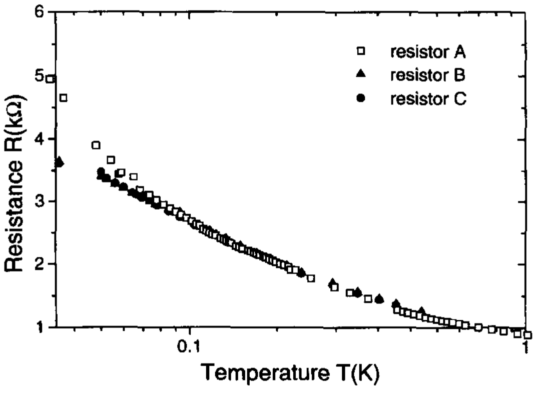

Figure 2 Resistance of resistors A, B and C as a function of temperature

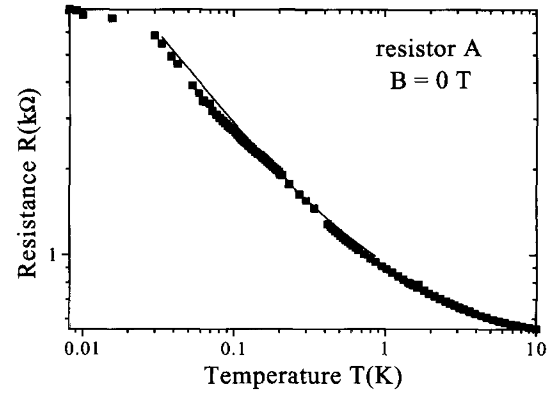

Figure 3 Temperature dependence of resistor A. Below 100 mK we superposed data from another resistor that was measured to 8 mK. No magnetic field is applied. The Earth's field is not compensated for. The continuous line is the fit to the data from Meisel *et al.*[4] for a similar resistor

Figure 4 shows the sensitivity function $\Delta R/\Delta T$ in the whole temperature range for the resistance A calculated after smoothing the data shown in *Figure 3*. The inset of *Figure 4* shows the absolute value of this function in a double logarithmic scale. The logarithm of the sensitivity function decreases approximately linearly with the logarithm of the temperature and follows $\log(|\Delta R/\Delta T|) \sim 0.5 - 1.63 \log(T)$ between 0.03 K and ~ 10 K.

Schoepe measured the temperature dependence of a RuO_2-based 10 kΩ resistance that follows a $\exp(T_0/T^{1/2})$ law below 4 K[5]. This behaviour is often observed in granular materials and might be attributed to variable-range hopping with Coulomb interactions[8] or hopping of electrons between metal grains[9]. In *Figure 5a* we plotted the logarithm of the resistance (resistor A) as a function of $T^{-1/2}$. Clearly, our resistor does not obey a $T^{-1/2}$ law in the whole temperature range. This dependence, however, is observed in the high-temperature range between 10 K and ~ 0.23 K. Interestingly, in this temperature range we can fit the data with $T_0 = 0.45$ K (straight line in *Figure 5a*) compared with $T_0 = 0.48$ K measured by Schoepe[5]. From this kind of plot (*Figure 5a*), we would speculate that a crossover to a different regime should occur at lower temperatures, $T < 0.23$ K.

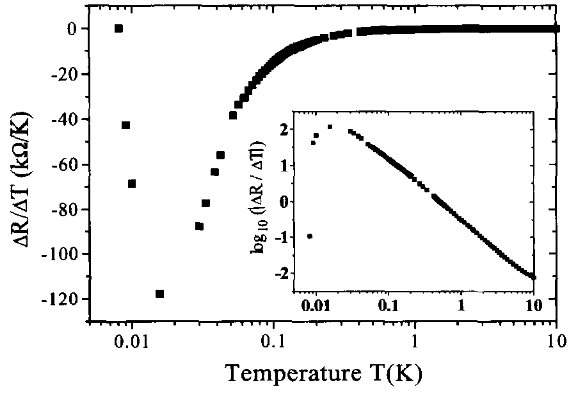

Figure 4 Sensitivity function or slope resistance *versus* temperature $\Delta R/\Delta T$ as a function of temperature of resistor A. The slope was calculated after smoothing the data shown in *Figure 3*. Inset shows the same data but in a double logarithmic scale

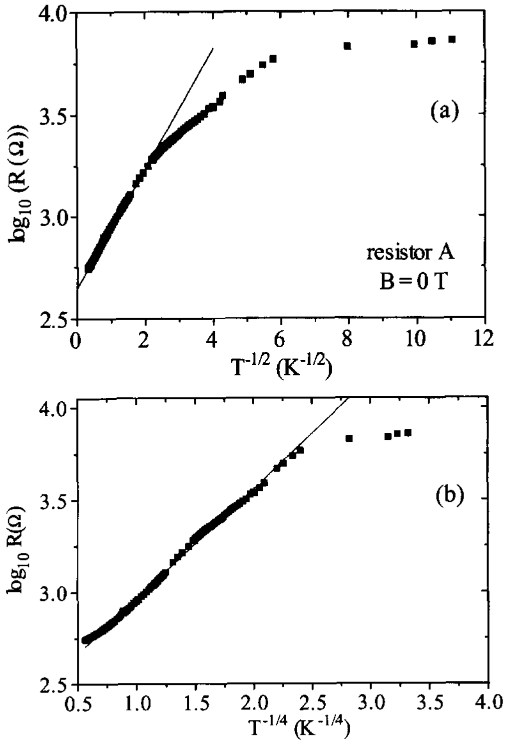

Figure 5 (a) Logarithm of the resistance of A *versus* $T^{-1/2}$. The solid line is obtained from the function $R \propto \exp(T_0/T)^{-1/2}$ with $T_0 = 0.45$ K. (b) Logarithm of the resistance of A *versus* $T^{-1/2}$. The solid line denotes the function $R = 0.257$ kΩ $\exp(1.3/T^{1/4})$

Figure 5b shows the same data as *Figure 5a* but plotted as a function of $T^{-1/4}$. Within ± 6% our data follow $R = 0.257$ kΩ $\exp(1.3/T^{1/4})$ (straight line in *Figure 5b*) at $0.03\ \mathrm{K} \leq T < 10$ K, in agreement with the dependence observed by Li and coworkers[3] for a 1 kΩ resistor. It is clearly seen in *Figure 5b* that the data oscillate with respect to the fit line. The reason for this is unclear. It can hardly be due to the calibration of the thermometers since several properties of different materials which show logarithmic and linear temperature dependences measured with the same thermometers showed no such an oscillatory behaviour.

As quoted by Li *et al.*[3], the $T^{-1/4}$ dependence can be interpreted as due to variable-range hopping conductivity, i.e. phonon-induced tunnelling of electrons between localized states[10,11]. Note that this dependence holds within 6% in almost the whole temperature range above 30 mK and our data do not confirm a $T^{-1/2}$ law, which would be expected due to hopping of electrons between metal grains[9] or as a consequence of the Coulomb interaction[8].

Magnetic field dependence

Figure 6 shows the field dependence of the resistors A, B and C at $T = 0.6$ K. For the three resistors the resistance increases with field. This behaviour is in clear contrast with the negative magnetoresistance of 1 kΩ resistors measured by Li *et al.*[3] and of 10 kΩ resistors measured by Schoepe[5] at the same temperature. The positive magnetoresistance might be interpreted as due to the orbital shrinking of the electronic wavefunction in a magnetic field and reveal that its long-range behaviour may be relevant for the electronic transport.

At temperatures below 1 K the resistance increases approximately linearly with magnetic field (see *Figure 6*). At these temperatures and within experimental error it is not possible to discern clearly a quadratic dependence at low fields. A fit to a second-order polynomial expression $R = R_o + R_1B + R_2B^2$ (R_i in kΩ, and B is the applied field in tesla) gives $R_o = 1.08$ (1.065, 1.08), $R_i = 9.07$ (7.7, 7.7) $\times 10^{-3}$, $R_2 = -2.86$ (+0.8, +0.77) $\times 10^{-4}$ for the resistors A (B, C). The difference in the field dependence between the three resistors is within experimental error and reproducibility. It is therefore difficult to be sure that the rather small negative curvature measured for the resistor A (see *Figure 6*) is due to its orientation with respect to the magnetic field. A negative curvature with field was also measured for a 1 kΩ resistor at 80 mK by Meisel *et al.*[4] and the overall change with field observed by these authors is similar to the one measured in this work.

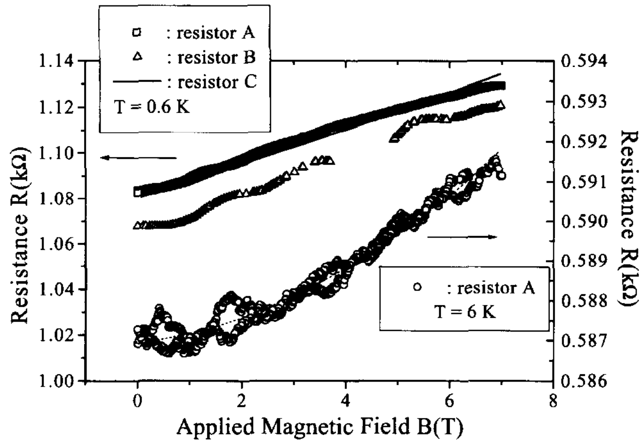

Figure 6 Field dependence of the resistors A, B and C at $T = 0.6$ K (left scale). The continuous line is a fit to the data of resistor C that is not shown for clarity. Right scale: the same for resistor A but at $T = 6$ K. The dashed line is a fit to the data. The data for the resistor A in the whole temperature range was taken by sweeping the field up and down

In *Figure 6* we also show the field dependence of the resistor A at $T = 6$ K. In contrast to the lower-temperature behaviour, the resistance shows an almost two orders of magnitude smaller linear term $R_1 = 1.73 \times 10^{-4}$, whereas the quadratic term is $R_2 = 7.47 \times 10^{-5}$. *Figure 7* shows the relative change of the resistance for a change of 1 T in field (from 0 T) as a function of temperature. The points at the same temperature were measured after cycling the resistor to room temperature.

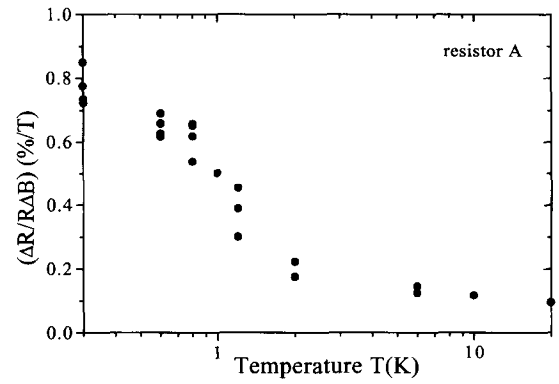

Figure 7 Relative change of resistance of resistor A divided by the corresponding change in magnetic field as a function of temperature for an applied field of 1 T. The different points at the same temperature were measured after cycling the sample of room temperature

Conclusions

The resistances of 500 Ω nominal resistors from the same batch manufactured by Dale Electronics were measured as a function of temperature and magnetic field. Above 100 mK the reproducibility of the temperature dependence is within 3%. One resistor (A) showed a temperature dependence (40 mK $\leq T \leq$ 750 mK) similar to that reported by Meisel *et al.*[4] with an absolute value approximately 7% smaller at 100 mK. Within the experimental error all measured resistors showed similar positive magnetoresistance independent of their orientation with respect to the magnetic field. The field dependence depends on temperature.

To summarize, the Dale RC-550 resistors are well suited for thermometers in the temperature range ~ 30 mK $\leq T \leq$ 10 K. Due to slightly different temperature and field dependences between resistors from the same batch, a previous calibration for accurately studies is unavoidable. Care should be taken if precise measurements with applied magnetic fields are needed.

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