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Full range resistive thermometers

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ABSTRACT

Resistive thermometers are widely used in low temperature physics, thanks to portability, simplicity of operation and reduced size. The possibility to precisely follow the temperature from room temperature down to the mK region is of major interest for numerous applications, although no single thermometer can nowadays cover this entire temperature range. In this article we report on a method to realize a full range thermometer, capable to measure, by itself, temperatures in the whole above-cited temperature range, with constant sensitivity and sufficient precision for the typical cryogenic applications. We present here the first results for three different full range thermometer prototypes. A detailed description of the set-up used for measurements and characterization is also reported.

1. Introduction

Resistive thermometers are widely used in cryogenics to monitor the temperature of experiments and samples. To date there is no single temperature sensor that can be operated over the whole 300 K–10 mK range and measure the temperature with high accuracy and precision. For resistive thermometers, this is related to: (a) the temperature dependence of the electrical resistivity of materials/compounds used to fabricate resistive thermometers and (b) the fact that precise commercial AC resistance bridges [1–3] can only reliably measure the resistance from few Ω up to few MΩ.

For example, ruthenium dioxide based thermometers (RuO_2) and ceramic zirconium oxynitride (CERNOX) thermometers are widely used for temperature measurements in the 10 mK–10 K and 1.5 K–300 K ranges, respectively [4–7]. The former cannot be used at high temperatures because the sensitivity vanishes and the latter cannot be used at low temperatures because the resistance rapidly assumes values larger than a few MΩ.

In this article we present a method to obtain a thermometer which operates in a range spanning from 10 mK to 300 K, with electrical resistances varying from few tens of Ω to hundreds of kΩ. The data and performances of three full range thermometers are presented, compared and discussed in relation with the currently available thermometers.

These new thermometers require a single four-wire measurement line, with an evident reduction of the costs of the experimental equipment (wiring, reading channels). They are of great interest especially in the case of dry dilution refrigerators, for which there are no temperature references between room temperature and 4 K, due to the absence of liquid nitrogen and liquid helium baths.

2. Full range technique, sample description and assembly

Fig. 1 plots the resistance as a function of temperature in the 10 mK–300 K temperature range for a typical Lakeshore CERNOX CX-1030-SD and Vishay $RuO_2@1k58$ thermometer. The resistance of the CERNOX sensor becomes higher than 100 kΩ for temperatures lower than 500 mK, and its measurement becomes difficult via commercial low temperature AC resistance bridges, whereas the sensitivity of the $RuO_2@1k58$ thermometer vanishes above 10 K.

The working principle of the full range thermometer was inferred from this plot. Indeed, combining the two resistances in parallel gives:

$$1/R_{\text{full range}} = 1/R_{RuO_2} + 1/R_{CERNOX}. \quad (1)$$

Such combination of different sensors in parallel can be found in the literature [8,9], but, as we will see, our set-up works on a wider temperature range, with an acceptable response time, and, most

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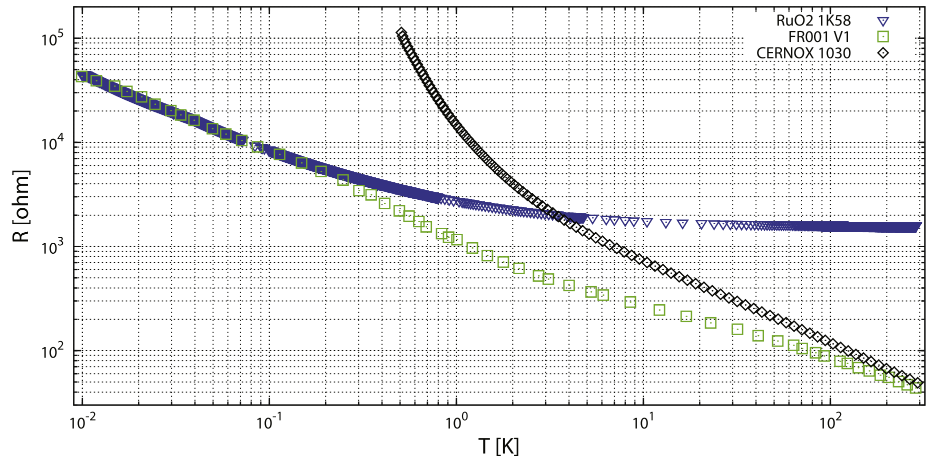

Fig. 1. Comparison between three typical thermometers: (a) $RuO_2@1k58$, (b) CERNOX CX-1030-SD and (c) full range sensor. Note that the RuO_2 has extremely low sensitivity for temperatures higher than few tens of K. The CERNOX thermometer exhibits large resistances for low temperature, which represents an issue for measurements done via commercial resistance bridges.

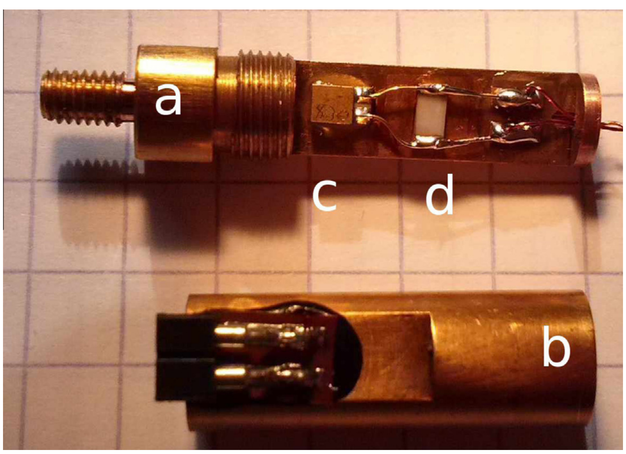

Fig. 2. Picture of the full range thermometer FR#001 mounting: (a) copper holder, (b) copper cap, (c) CERNOX CX-1030-SD and (d) $RuO_2@1k58$ thermometer. The thermometers are electrically coupled in parallel. The side of a square is 5 mm.

importantly, with an almost constant sensitivity. At high temperature, the resistance of the $RuO_2@1k58$ is much larger than the resistance of the CERNOX and $R_{full\ range} \sim R_{CERNOX}$ (CERNOX-like behavior). *Vice-versa*, at low temperatures, the CERNOX resistance becomes much larger than the $RuO_2@1k58$ resistance and hence $R_{full\ range} \sim R_{RuO_2}$ (RuO_2-like behavior). The cross-over point for the specific combination of thermometers reported in Fig. 1 is around 3 K, where their resistances are equal.

With these general considerations, one can play with different CERNOX and RuO_2 thermometer types and realize different "full range" sensor families, exhibiting different sensitivities or resistance values best adapted to the specific experimental needs.

Fig. 2 shows the assembly of the first full range thermometer prototype, FR#001. A $RuO_2@1k58$ thermometer and a commercial CERNOX CX – 1030 – SD are electrically coupled in parallel. Both the RuO_2 and the CERNOX chips are glued via a 10 μm GE-Varnish film on the thermometer copper holder (see [10]). A copper cap encapsulates the thermometer copper holder and screens the chips from infrared radiation, avoiding spurious overheating. We realized and tested three full range thermometers. All of them adopted a $RuO_2@1k58$ chip. The FR#001 and FR#002 used a CERNOX CX-1030-SD, whereas the FR#003 thermometer used a CERNOX CX-1050-SD.

3. Calibration set-up

These three full range thermometers have been studied at SPEC/CEA cryogenic laboratory in a dry dilution refrigerator [11]. They have been thermally cycled to liquid nitrogen temperature several time before calibration. They have been mounted on a *OFHC* copper holder, which also hosted several reference thermometers. The list below reports our temperature references in the whole 300 K–10 mK range:

- Lake Shore CERNOX 1050 type: calibrated by the manufacturer (Lake Shore) in the range 300 K–1.5 K. Typical accuracy $\frac{\Delta T}{T}$ is better than 0.1%.
- SRD1000 fixed point device and CMN – 225 paramagnetic salt thermometer [12]. The paramagnetic salt was used in the temperature range 1.18 K–6 mK and was in situ calibrated via SRD1000 fixed point references.
- Lake Shore germanium sensor GR-200A-50-1.15A (Ref. Num.: 30671), calibrated by the manufacturer in the range 4 K–50 mK. Typical accuracy ΔT is better of about 5 mK over the whole range.
- A $RuO_2@1k58$ thermometer, assembled and previously calibrated in the laboratory in the range 10 K—10 mK. This thermometer is also used for comparison with the full range thermometers.
- ^{60}Co nuclear orientation thermometry, to cover the range from 40 mK–10 mK. A Canberra HP:Ge detector GC1018, placed at a distance of about 400 mm from a ^{60}Co needle of 40 kBq activity, measured the nuclear moment anisotropy. Typical accuracies are: 0.5 mK for temperatures lower than 20 mK, increasing up to 3 mK at 40 mK.

The temperature range of the different thermometers overlapped and allowed us to cross-check the consistency of our temperature references. For all the three full range thermometers, a correspondence between their resistance and our set of temperature references (calibration) has been established. The resistance measurements have been performed via a TRMC2 high precision low excitation AC resistance bridge [13].

Calibration points in the high temperature range ($T \geqslant 4$ K) have been acquired during the cool-down of the cryostat, which takes 12 h. At such low cooling speed, no thermal gradient within the copper holder was observed. For low temperatures ($T < 10$ K), the calibrations have been established by setting the mixing chamber via PID regulation at different fixed temperature values