DIRECT RESISTANCE COMPARISONS FROM THE QHR TO 100 MEGOHM USING A CRYOGENIC CURRENT COMPARATOR

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Abstract

We describe the operation of a cryogenic current comparator (CCC) bridge that attains high current sensitivity while maintaining stability under a range of measurement conditions. Measurements of 100 MΩ standard resistors and cryogenic thin-film resistors have been made at low voltage levels, based directly on a quantized Hall resistance (QHR) standard.

Overview and Background

Single-electron tunneling (SET) experiments have begun to stimulate research into highly sensitive cryogenic detectors capable of measuring very small dc currents. Some of these measurement methods utilize superconducting quantum interference device (SQUID) current detectors, and are similar to the CCC systems that have been employed in precise comparisons of resistance standards using the Josephson voltage standard [1] and more recently and widely using the QHR standard [2-3].

In applying these methods, the ratio of CCC windings is often a critical parameter and the number of windings must be as large as possible to attain the highest resolution for very small currents. In order to detect the current from today's SET devices with high precision, a CCC would require tens of thousands of turns of small diameter wire as well as a large winding area, producing undesired but substantial self-inductance in the primary winding. Together with stray internal capacitance, this could result in an impedance resonance in the audio frequency range and have negative effects on the stability and sensitivity of the SQUID and bridge system.

CCC design and behavior

A CCC of a special design enables us to compare high resistance values against the QHR standard by using multiple connections and a superconducting secondary winding [4]. The CCC of this study, with a 15 496 turn primary, has a transfer function of approximately 240 pA/Φ_0 with a commercial dc SQUID, and a sensitivity of 3.75 µA turn/Φ_0. The primary winding consists of 76 µm diameter phosphor-bronze wire and has a resistance of about 60 kΩ at 293 K and 47.949 kΩ at 4.2 K. The design is similar to a CCC bridge described in [4]. That earlier CCC has a similar winding geometry but 1927 turns of superconducting wire in the primary winding. The purpose of using resistive wire here is to damp the internal LRC circuit [5], the effect of which can be observed in the noise spectra (Fig. 1) of the earlier, fully superconducting CCC bridge.

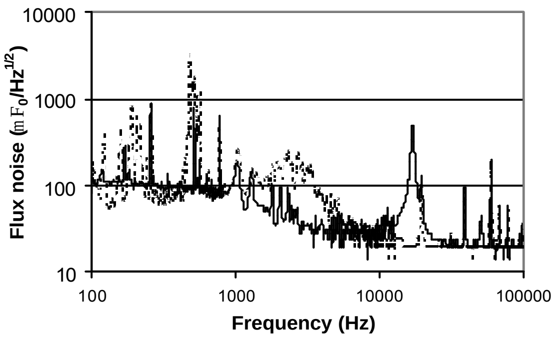

Fig. 1. SQUID flux noise spectra for two similar CCC bridge systems. The dotted line represents the resistive-winding CCC for 100 MΩ, while the solid line represents the superconducting-winding CCC for 1 MΩ standards.

The SQUID electronics cause the signal to roll off above 1000 Hz, however Fig. 1 shows a resonance in the SQUID flux noise near 18 kHz for the 1 MΩ CCC. Both systems have various narrow, low- and high-frequency peaks in the noise due to the SQUID electronics, poorly damped mechanical vibrations, and harmonics of the power frequency. The higher-ratio CCC also has a broad region of noise centered near 2500 Hz, and a region of noise near 500 Hz, but the magnitude of the voltage fluctuations in these regions is substantially less than observed in the 1 MΩ CCC resonance. The secondary winding of each bridge system was connected to the QHR standard when the data shown in Fig. 1 was obtained. In these noise measurements, the primary resistors in the two bridges consisted of a thin-film chromium cryogenic resistor of

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value 97.2 MΩ connected inside the cryostat of the 100 MΩ CCC, and a room temperature 1MΩ wire-wound resistance standard for the 1 MΩ CCC.

The performance of the two systems is similar, even though the current sensitivity of the 100 MΩ system is slightly more than eight times higher. Neither CCC system attains the expected level of noise performance, based on the quoted noise levels of the SQUID sensors (≈3 $\mu\Phi_0/\sqrt{Hz}$ at 100 Hz) and the Johnson noise generated in the resistors (8 $\mu\Phi_0/\sqrt{Hz}$ for the cryogenic resistor and 7 $\mu\Phi_0/\sqrt{Hz}$ for the wire-wound 1 MΩ resistor). When an external, room temperature 100 MΩ standard (67 $\mu\Phi_0/\sqrt{Hz}$) is used in place of the cryogenic thin-film resistor little change in the noise floor is observed, although the lower frequency peak amplitudes increase, probably as a result of the pickup and vibrations of the additional wiring.

Resistance Comparisons

Lead resistance in the primary arm of these two-terminal CCC bridges is a significant measurement offset for resistance comparisons, so the resistance alloy used in the CCC must have a low temperature coefficient and its resistance must be small and easily measurable compared to the value being calibrated. Also, in order to analyze the high resistance CCC data, one must calculate the primary current and final resistance value by a quickly converging iterative process.

The two CCC bridges allow us to compare Hamon-type networks configured both as 1 MΩ and 100 MΩ resistance standards. Using an applied guard voltage [6], CCC scaling results agree well with the traditional high-resistance Hamon scaling technique for most of the standards used, and leakage effects are suspected in the one device where a difference is observed. The guarding technique is essentially ideal for two-terminal standards, but can cause errors when leakage occurs at terminations within the high resistance Hamon devices.

Chromium thin-film resistors were deposited as a meander pattern on insulated Si wafers. At cryogenic temperatures these high-resistance samples have large negative temperature coefficients. Their resistance when compared to the QHR standard using the new CCC correlates with barometric pressure (and thus bath temperature) of the liquid helium bath (see Fig. 2).

In this type of CCC bridge, some connection points between the current source, standards, and windings must be superconducting, and voltage fluctuations may occur if the liquid level falls below the critical

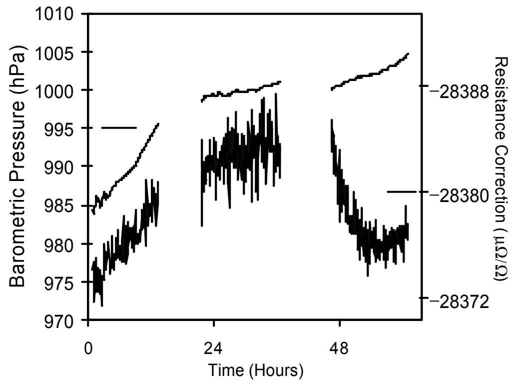

Fig. 2. The measured resistance of a 97.2 MΩ chromium thin-film resistor at 4.2 K compared to the laboratory barometric pressure. The liquid helium in the cryostat was refilled at around 40 hours in this sequence.

connections at these points. We believe this is seen in the second group of data in Fig. 2. Liquid helium level similarly affects the noise in room temperature 100 MΩ resistance measurements with the CCC below the same liquid helium level. Details of the CCC performance are being studied and will be presented at the conference.

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