Pressure Dependencies of Standard Resistors

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Abstract

The U. S. representation of the ohm is based on the quantized Hall resistance of 6453.20175 Ω with a combined standard uncertainty of 0.02 ppm. To maintain the ohm at this resistance or other resistances at this uncertainty level requires well-characterized standard resistors. A sometimes overlooked parameter affecting standard resistors is pressure. A variety of standard resistors are examined for pressure dependencies over the range 250 hectopascals (hPa) above and below a standard atmosphere. Results indicate that the pressure coefficients of resistance for some standards are significant.

Introduction

At the National Institute of Standards and Technology (NIST), the U. S. representation of the ohm is based on the quantum Hall effect[1] in which a resistance is related to the ratio of fundamental constants h/e^2. The quantized Hall resistance (QHR) step of 6453.20175 Ω is usually chosen to establish the value of the U. S. ohm. This odd resistance value, along with the complexity of the experiment, does not lend itself to the routine support of the calibration of standard resistors of nominal decade values. Therefore, at NIST the ohm is maintained for calibration purposes at 1 Ω via a group of five Thomas-type resistors whose predicted mean value is checked periodically (usually every four months) against the QHR and adjusted, if necessary. The combined standard uncertainty of comparing this 1 Ω working group with the QHR is estimated to be within 0.02 ppm[2]. NIST also maintains a working reference group at each nominal decade value from 0.1 Ω to 10 GΩ. These working reference groups are calibrated against the 1 Ω reference group using special ratio techniques[3].

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Aside from assigning resistance values in terms of the QHR, the uncertainties associated with maintaining the ohm at the various decade resistances depends on the ability to predict the values of the standard resistors in the working groups as a function of time and changes in environmental conditions. The change of resistance of a standard resistor with time can be determined from the data obtained from several comparisons of its value against the QHR. These experimental data provide evidence that, over a time period of a year or more, the stability curves of resistors can be modeled as linear functions with residual standard deviations of < 0.01 ppm. The main environmental influence factors of concern with resistors are temperature, humidity, and pressure. Changes in the temperature of a resistor can be controlled and/or measured with sufficient precision to correct for its influence. Problems associated with changes in humidity and pressure are thought to be eliminated by hermetically sealing the resistance element in its container. However, the desire to provide good thermal contact between the resistance element and the surrounding medium has resulted in the use of thin-walled containers and, as a consequence, significant pressure coefficients of resistance (PCRs) for some resistors.

This paper summarizes the PCR determinations of Thomas-type resistors accumulated over the years at NIST. New results are presented on the PCRs of 6453.2 Ω and 10 kΩ standard resistors. Also included are preliminary results of PCR measurements on 100 Ω standard resistors.

Background

Although the investigations of the effects of pressure on the electrical resistance of metals have been underway since prior to 1900, a precise quantitative understanding or theory on this subject is still lacking. For a "normal" metal, the electrical resistance is expected to decrease with increasing pressure. This results because increasing pressures reduce the amplitude of lattice vibrations in the metal, and its resistivity is directly proportional to the mean square amplitude of the lattice vibrations(4). However, some pure metals and alloys exhibit anomalous behavior such as a decrease, or a minimum, or a maximum, or a step-like structure in resistance with increasing pressure that cannot be readily explained. Qualitative interpretations conclude that the PCRs of metals are highly sensitive to the exact details of the distortion in the Fermi surfaces and the electron-phonon interaction mechanisms - subject matter beyond the scope of this paper.

Of interest are the PCRs of manganin and Evanohm* resistance alloys used in the construction of standard resistors. Manganin has a composition of approximately 84% Cu, 12% Mn, and 4% Ni with a resistivity of ≈ 48 μΩ•cm and generally is used in the construction of standard resistors of values less than 100 Ω. Its PCR is

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*Evanohm is the trade name of a commercial resistance alloy developed around 1948 by the Wilbur B. Driver Company.

dependent on the heat-treatment condition of the wire and is ≈ 2.3 ppb/hPa[5], where ppb refers to part-per-billion (10^9). The composition of Evanohm is approximately 75% Ni, 20% Cr, 2.5% Al, and 2.5% Cu with a resistivity of ≈ 110 μΩ•cm. It is used in the construction of standard resistors of values 1 Ω or larger. The electrical resistance of Evanohm wire has been determined as a function of hydrostatic pressure and found to be ≈ -1.1 ppb/hPa[6].

Experimental Results

Thomas-type 1 Ω Resistors - The Thomas-type resistors were developed in 1933[7] and constructed of #12 AWG manganin wire wound on a 8-cm diameter metal form and annealed at about 550 °C in a vacuum. The rigid resistance coil was slipped onto a silk-insulated inner cylinder of a double-walled container, spaced and tied down with linen thread, shellacked and baked for an hour at about 80 °C. The resistance coil was sealed in dry air within the 1 cm annular space between the two coaxial brass cylinders. With the resistance coil mounted tightly in contact with the inner cylinder, any variations in atmospheric pressure tend to expand or compress the walls and thus apply stresses to the coil. Figure 1 is a histogram of NIST PCR determinations on 12 original Thomas resistors that were constructed in 1933 and 34 commercial Thomas-type resistors. Results indicate that the PCR values for Thomas-type resistors constructed with manganin wire are all positive.

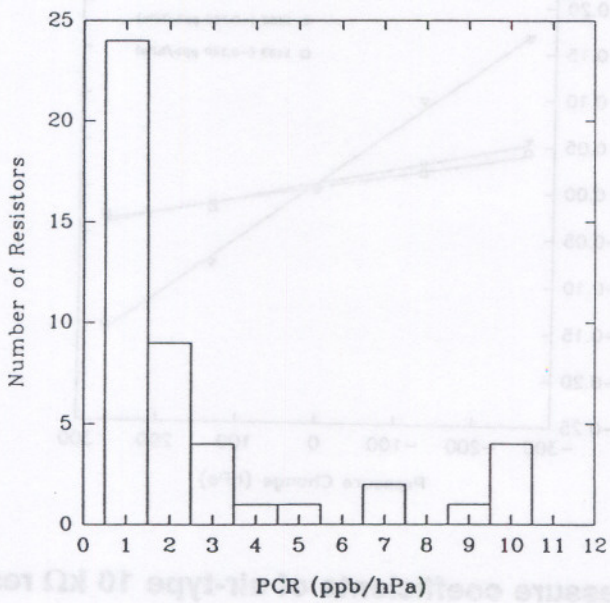

Figure 1. Pressure Coefficients of Thomas-type resistors.

All the PCR values of the original Thomas resistors were over 2 ppb/hPa. The commercial Thomas-type resistor had PCR values all under 2.5 ppb/hPa. After disassembling an original and a commercial Thomas-type resistor, it was observed that the makers of the commercial type did not shellack the coil nor tie down the coil as tightly as was done in the original Thomas resistor, which may explain the significant difference in PCR values. For a user located at an altitude of 1.6 km above sea level, the resistance of a Thomas-type resistor with a PCR of 1 ppb/hPa would be 0.2 ppm less than the value at the altitude of the NIST Gaithersburg Laboratory.

<u>Special 10 kΩ Standard Resistors</u> - These commercially available resistors[8] are constructed of Evanohm alloy and usually exhibit small corrections (< 10 ppm from nominal), low drift rates (< | 0.2 | ppm/year), and low temperature coefficients of resistance (0 ± 1 ppm/K). They are either designed for operation in an oil bath at 25 °C or in a laboratory air environment at 23 °C. The oil-type resistors are housed in cylindrical containers with external dimensions similar to a Thomas-type resistor. Measurements indicate that these 10 kΩ resistors do not have a significant PCR (< | 0.05 | ppb/hPa). However, measurements on the air-type 10 kΩ resistors indicate they have negative values of PCR. These resistors are constructed of Evanohm wire wound on mica cards and hermetically sealed in oil in a rectangular container of approximate dimensions 17.5 cm x 8.5 cm x 9.5 cm with 1 mm wall thickness. Figure 2 is a plot of pressure coefficients for three 10 kΩ air-type standard resistors. The solid lines are obtained from a least-squares analysis of the data. The slopes of the lines indicate the PCR values of the resistors.

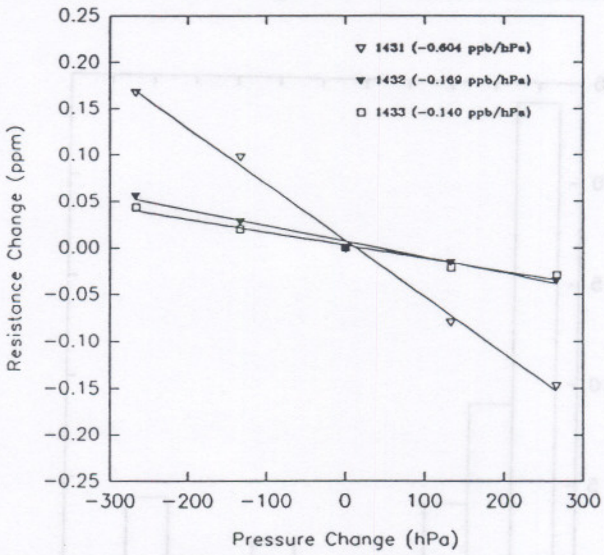

Figure 2. Pressure coefficients of air-type 10 kΩ resistors.

The PCR was determined for the main resistance element of an air-type 10 kΩ resistor, removed from its hermetically sealed container. The resistance element was placed in a pressure cell filled with mineral oil for these measurements. This result should indicate a PCR value that is greater than the absolute value for sealed resistors of this type. Figure 3 is a resulting plot of these measurements along with the fitted least-squares line.

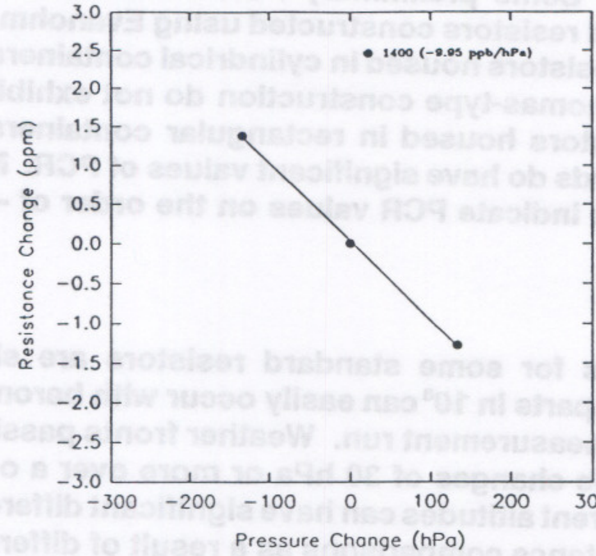

Figure 3. PCR of unsealed 10 kΩ resistor.

<u>Special 6453.2 Ω Resistor</u> - Resistors are commercially available that have a value equal to the QHR step of nominal value 6453.2 Ω. These resistors are similar in construction to the air-type 10 kΩ standard resistors. Results of PCR measurements and corresponding fitted lines of five resistors of this type are shown in Figure 4. Since these resistors are constructed with Evanohm wire, their PCRs are also negative.

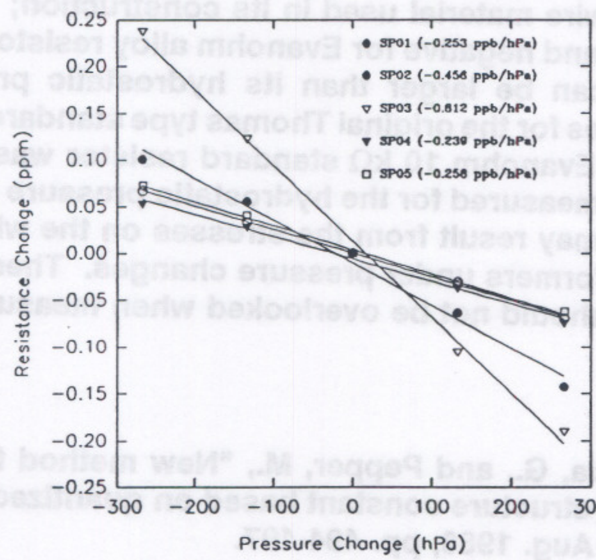

Figure 4. Pressure coefficients of 6453.2 Ω resistors.

100 Ω Standard Resistors - Some preliminary PCR determinations have been completed on 100 Ω standard resistors constructed using Evanohm wire. Results indicate that oil-type 100 Ω resistors housed in cylindrical containers with external dimensions similar to the Thomas-type construction do not exhibit a significant PCR. However, 100 Ω resistors housed in rectangular containers of the same dimensions as 10 kΩ standards do have significant values of PCR. Measurements on two resistors of this type indicate PCR values on the order of -0.9 ppb/hPa.

Conclusion

The pressure dependencies for some standard resistors are significant, i.e., resistance changes of a few parts in 10^8 can easily occur with barometric changes of 10 hPa or more during a measurement run. Weather fronts passing through an area can result in barometric changes of 30 hPa or more over a one-day period. Laboratories located at different altitudes can have significant differences (as large as 0.2 ppm or more) in resistance comparisons as a result of different barometric pressures.

The PCR of a resistor is highly dependent on its design and construction. Hermetically sealing its resistance coil in a container does not ensure that a standard resistor will have a negligible PCR. As expected, the closer the resistance coil is mechanically coupled to its container (as with the Thomas-type resistors), the greater in magnitude the value of its PCR. For standard resistors designed to have a relatively free-standing resistance coil, the cylindrical container construction is more rigid resulting in lower or negligible values of PCR.

The sign of the PCR of a resistor follows the sign of the hydrostatic pressure dependence of the bare wire material used in its construction; it is positive for manganin alloy resistors and negative for Evanohm alloy resistors. However, the magnitude of the PCR can be larger than its hydrostatic pressure value as indicated by the PCR values for the original Thomas type standards. Also, the PCR of an unsealed, air-type, Evanohm 10 kΩ standard resistor was measured to be about 10 times the value measured for the hydrostatic pressure of bare Evanohm wire. This large change may result from the stresses on the wire caused by the deformation of the mica formers under pressure changes. These effects caused by changes in pressure should not be overlooked when measuring resistors.

References

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