The Design, Construction, and Performance of a Wide Range of DC Conductance Bridge

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Abstract—**A dc conductance bridge for laboratory use is described which embodies a combination of features not found in any other bridge. The range of measurement extends from 10^{-15} mho to 1 mho, and the minimum detectable change in conductance is 4×10^{-16} mho. Bridge voltages of 6, 45, and 135 volts may be applied. Since the highest resistance arm is only 10^7 ohms, the time constant of the bridge is small and the effect of leakage in shunting an arm is very small. By virtue of a specially designed terminal block, guarded and shielded measurements can be made at, or remotely from, the bridge terminals. Provision has been made for performing both grounded and direct conductance measurements. For high conductance measurements, a zero balance circuit has been incorporated to compensate for lead resistance. The resolution is ten parts per million from 1 mho to 10^{-9} mho. The bridge performance was studied employing individual calibrated resistances, and low conductance wye networks fabricated from these components. The accuracy is better than 0.05 percent from 1 mho to 10^{-8} mho, about 1 percent at 10^{-12} mho, and 5 percent at 10^{-14} mho.**

Introduction

THE EXPERIMENTAL investigation of conductivity phenomena in semiconducting and insulating materials has in the past usually been carried out by measuring resistance and then performing the conversion to conductance. This technique generally employs a Wheatstone-type bridge. This bridge, however, either does not cover a sufficiently wide range of resistance or, of necessity, contains very high and generally unreliable resistances in the standard arm. In addition, measurements with the latter type bridge are complicated by inherently long time constants associated with the high resistance components in the bridge circuit. These limitations were overcome in a modified Wheatstone bridge[1] with a resistance range of 1 ohm to 10^{15} ohms.

Notwithstanding these advances in the art of resistance measurements, the direct measurement of conductance of dielectrics and semiconductors has distinct advantages. For example, in multicrystalline bodies conduction is essentially a parallel path mechanism, and, therefore, conductance is a more logical measurement. Also, the conductivity, both ac and dc, is very often more significant than resistivity in the investigation of these materials.

The bridge described here measures conductance directly and has a combination of features not found on any other bridge. 1) It has a conductance range from 1 mho to 10^{-15} mho and the minimum detectable conductance is 4×10^{-16} mho. 2) It has high accuracy; the error is less than 0.05 percent at 1 mho, about 1.0 percent at 10^{-12} mho and 5 percent at 10^{-14} mho. 3) Guarded and shielded measurements can be made at, or remotely from, the bridge terminals. 4) Provision has been made for performing both grounded and direct conductance measurements. 5) The standard arm employs a series of resistance decades which permits a resolution of ten parts per million for conductances from 1 mho to 10^{-9} mho.

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[1] H. A. Sauer and W. H. Shirk, Jr., "A dc Wheatstone bridge for multi-terohm measurements with high accuracy capability," *IEEE Trans. on Communications and Electronics*, vol. 83, pp. 131–136, March 1964.

The Conductance Bridge

The basic circuit of the conductance bridge is given in Fig. 1. At balance the relationship between the conductance G_x of the unknown and the resistance R_s of the standard is

$$G_x = \frac{R_s}{R_{AD}R_{BC}} = KR_s$$

where R_{AD} and R_{BC} are the resistances of the AD and BC arms respectively, and K, the product arm setting, equals $(R_{AD}R_{BC})^{-1}$. In the complete circuit, Fig. 2, the range resistors in the AD and BC arms are ganged in the manner indicated to provide K values ranging from 10^{-14} to 10^{-4} mho^2. The standard arm contains six resistance decades providing a total resistance R_s of 11 111.1 ohms. The individual resistors in the arms and standard have accuracies ranging from 0.01 to 0.03 percent. The guarded battery, connected to the A and C corners through a guarded switching circuit, supplies to the bridge fixed voltages of 6, 45, and 135 volts of either polarity. The voltage across a 1 mho sample is about 1 percent of the applied bridge voltage; for a 10^{-14} mho sample, the voltage across the sample is equal to the bridge voltage. The detector, a Boonton Electronics Model 56A, is connected across the B and D corners through a switch which allows either the D or the B corner to be grounded. When D is grounded, the X_2 terminal of the test specimen is at ground potential, and the measured conductance includes all conductances from the X_1 specimen terminal to ground. When B is grounded, the specimen's direct conductance from X_1 to X_2 is measured. In this case leakage from X_1 to ground must be kept much smaller than the conductance of the BC arm. The effect of this leakage can be checked by repeating the measurement with a K value which uses a different value for R_{BC}.

A zero balance circuit, shunting the R_s arm, has been included to compensate for resistance in series with the unknown. This circuit is used in the measurement of large conductances for which lead resistance could cause appreciable error. Adjustment of the circuit is made with the R_0 switch set at "ADJ" and the X_1-X_2 terminations shorted. With K set at 10^{-4} position, the bridge is then balanced with the R_0 ADJ dials. With R_0 set at "MEAS" and $K=10^{-4}$, the bridge then reads the true value of G_x without further lead correction.[2]

The performance and accuracy are related to the following important aspects in the bridge design. The impedance seen by the detector is small, which results in greater sensitivity for a given detector. The highest resistance arm is only 10^7 ohms, and hence the effect of leakage shunting an arm is very small. Also, these low resistance arms make the time constant of the bridge small. The leakage across the bridge terminals is easily measured as an open circuit conductance. In high conductance measurements a correction for lead resistance, by a short circuit balance, is easily made as described in the previous section. The use of six decades for the standard permits high readability.

The bridge was constructed in accordance with our specifications by the Leeds and Northrup Company, Philadelphia, Pennsylvania, and is shown in Fig. 3. It is completely shielded from extraneous electrostatic pickup. Internally, the detector is shielded from the rest of the bridge circuit. The terminal block consists of three Hirschmann VST-20 banana plugs mounted in a Teflon disk. Two conductors are the X_1-X_2 terminals; the other conductor is the guard which is connected to the A terminal of the bridge. An easily removable cylindrical cup over the terminal block serves as both a dust cover and an electrostatic shield. With shielded fittings, measurements can be made at any convenient distance from the bridge. A guarded switch and check meter aid in determining the condition of the bridge voltage supply. Access to the battery and to the internal bridge structure can be made from both the side and rear of the cabinet. Figure 4 is a view of the bridge through the rear entry. The bridge proper is mounted on the front panel, Fig. 5, and can be removed for inspection or repair purposes simply by disconnecting the detector, battery leads, and the cables to the terminal block. Figure 6 shows the terminal block.

Bridge Performance

Two experimental wye configurations and their component resistors were measured to check the reproducibility and accuracy of the bridge. The wye networks through their delta transformations provided simulated conductances of 10^{-12} and 10^{-14} mho. The wye networks were so constructed that no solid insulation not already part of the bridge was used. A further feature of this construction was that the resistance of the individual resistors could be measured without removing, exposing, or in any way handling or disturbing the wye structure. Briefly, this was accomplished by supporting the network in a metal housing in such a manner that the supports could be freed from the network after it was plugged into the bridge terminals. By the use of special adaptors, individual resistors could be isolated from the network and measured.

In the three-terminal measurements with very low conductance networks in which the wye structure is connected to the A, X_1, and X_2 bridge terminals, it was difficult to make a D grounded measurement. The unsatisfactory operation of the bridge is related to an extensive capacitance coupling between the guard circuit and those portions of the bridge circuit which are at ground potential.[3] The buildup of charge on this guard to ground capacitance introduces a spurious voltage unbalance, hence an erroneous detector deflection.

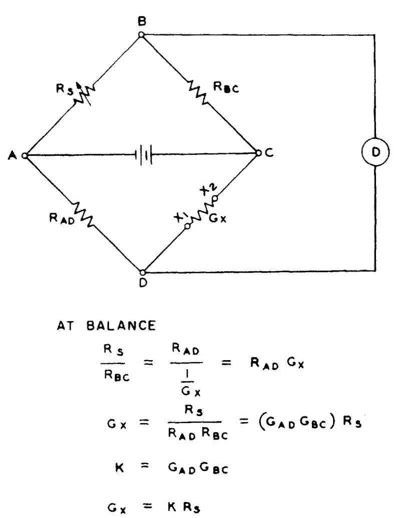


Fig. 1. Basic circuit of dc conductance bridge.

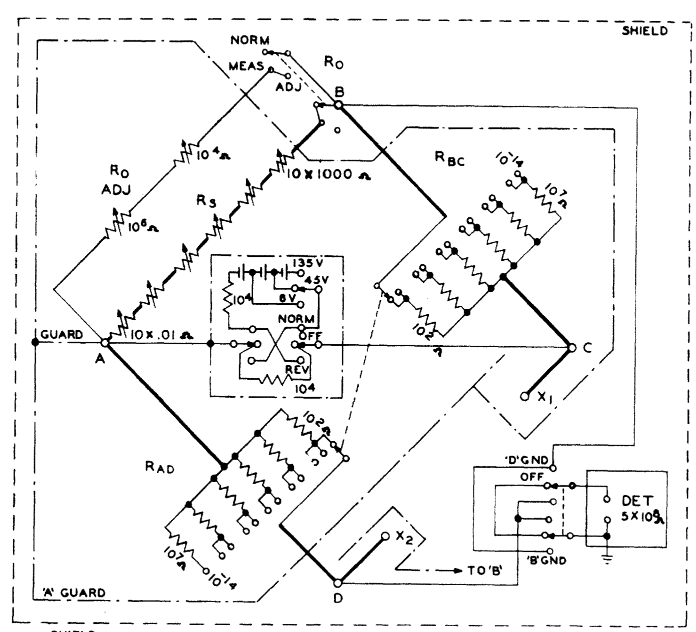


Fig. 2. Complete circuit.

[2] On occasion it may be necessary to perform this check at $K=10^{-5}$ setting. However, such a check is of no consequence at the remaining K settings.

[3] L. C. Fryer, Leeds and Northrup Company, Philadelphia, Pa., June 25, 1963, private communication.

Fig. 3. Conductance bridge assembly.

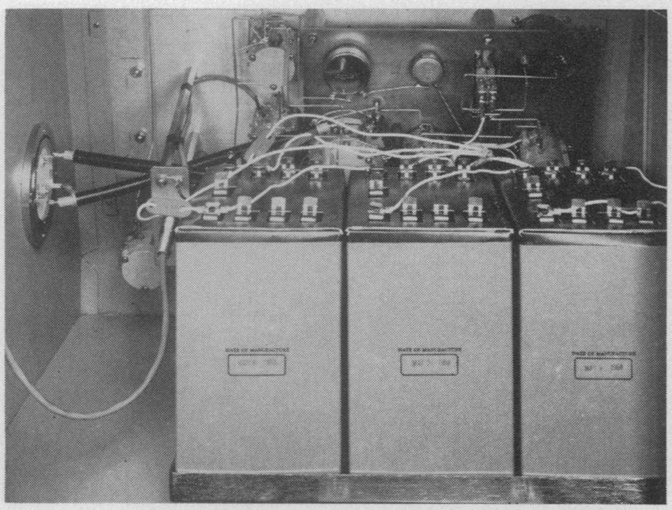


Fig. 4. Rear entry view of bridge.

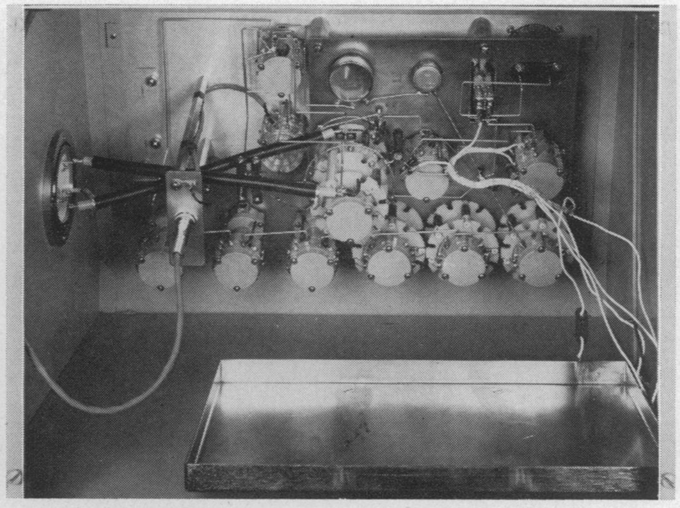


Fig. 5. Rear entry view with batteries removed.

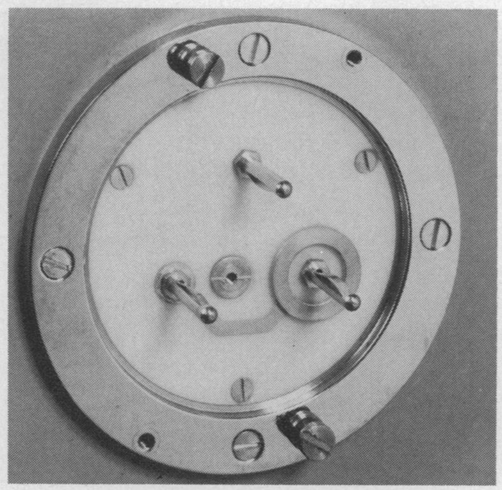


Fig. 6. Exterior view of terminal block.

Under this condition a null-point bridge balance requires an R_s setting which reflects an incorrect value for the simulated resistance across the X_1-X_2 terminals. It is emphasized that this measurement difficulty occurs only when "D" is grounded and the value of the "X" resistor is extremely high. When "X" is 10^{14} ohms and "D" is grounded, the error signal is caused by the flow of capacitor charging current through the "X" resistance, and this resistance is so large that it reduces the charging current to such an extent that the error signal persists for a long period. When "B" is grounded, the capacitance charging current flows through the product arm BC which cannot exceed 10^7 ohms. The error signal in this case is only, in effect, 10^{-7} times as long; i.e., the period is so short that the error signal is not perceptible.

Introduction of the wye network into the bridge circuit, of course, changes the value of the product arm setting. In the case of the network required to simulate a 10^{-12} mho conductance across the X_1-X_2 terminals, this change is less than 0.1 percent; for a wye simulating a 10^{-14} mho conductance, the change is less than 1 percent.

Table I presents a summary of the measurements on the wye networks and their individual resistors. The resistors, identified by their nominal value, were measured at two product arm settings under the conditions of 24°C and 25 percent RH. The tests were conducted alternately with D terminal grounded and then with B terminal grounded. It is seen that reproducible measurements were obtained at both K settings with either the B corner or the D corner grounded. The resistors were measured under the conditions of 23°C and 30

TABLE I
Conductance Bridge Calibration Wye Components

Network	Nominal Resistance Ohms	Applied Bridge Voltage	K	"B" Ground	"D" Ground	Bridge Accuracy Percent	BTL Measured "B" Ground	NBS Calibrated	NBS Accuracy Percent	$\frac{\text{NBS-BTL}}{\text{NBS}}$ Percent
	1×10^6	135	10^{-8}	1.0000×10^{-6}	1.0000×10^{-6}	±0.05				
			10^{-9}	1.00008×10^{-6}	1.00008×10^{-6}	0.05	0.99992×10^6	1.000063×10^6	0.002	0.014
10^{12} Ohms	1×10^9	135	10^{-11}	919.0×10^{-12}	919.0×10^{-12}	0.3				
			10^{-12}	917.70×10^{-12}	917.70×10^{-12}	0.6	1.0897×10^9	1.0906×10^9	0.2	0.09
	1×10^9	135	10^{-11}	927.5×10^{-12}	927.2×10^{-12}	0.3				
			10^{-12}	926.10×10^{-12}	926.00×10^{-12}	0.6	1.0798×10^9	1.0822×10^9	0.2	0.24
	1×10^4	45	10^{-6}	99.99×10^{-6}	99.99×10^{-6}	0.05				
			10^{-7}	99.994×10^{-6}	99.994×10^{-6}	0.05	1.00006×10^4	1.000136×10^4	0.002	0.008
10^{14} Ohms	1×10^9	135	10^{-11}	913.8×10^{-12}	913.8×10^{-12}	0.3				
			10^{-12}	912.55×10^{-12}	912.55×10^{-12}	0.6	1.0943×10^9	1.0974×10^9	0.2	0.31
	1×10^9	135	10^{-11}	892.4×10^{-12}	892.6×10^{-12}	0.3				
			10^{-12}	891.17×10^{-12}	891.19×10^{-12}	0.6	1.1221×10^9	1.1235×10^9	0.2	0.14

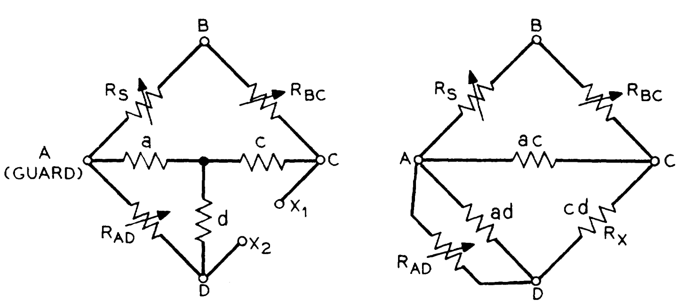
Wye Networks

Nominal Conductance	Applied Bridge Voltage	K	Bridge Accuracy R_s	Bridge Accuracy Percent	Calculated Bridge Reading R_s NBS	$\frac{\text{NBS-BTL}}{\text{NBS}}$ Percent
1×10^{-12}	135	10^{-14}	83.70	±1.0	83.80	0.12
1×10^{-14}	135	10^{-14}	0.83	5.0	0.80	3.8

percent RH by the National Bureau of Standards. The resistances, calculated from the conductance measurements are compared with NBS calibrated values.[4] In the wye measurements the bridge balance readings R_s are compared with the values calculated from the NBS calibration of the individual components for the particular wye network. The bridge accuracy for the different conductance ranges is obtained from L & N Spec. 1792-95 covering this bridge. The agreement between the BTL and NBS results is found in all cases to be within the combined accuracies of the conductance bridge and the NBS measurements.

Appendix

Calculation of Bridge Reading (R_s) Using NBS Calibrated Values for $10^{12}\ \Omega$ Simulated Resistance



ACTUAL CIRCUIT EQUIVALENT CIRCUIT

[4] The procedure for calculating R_s from the NBS calibrated values for the simulated 10^{12} ohm resistor is outline d in the Appendix.

NBS Values (in ohms)

$$a = 1.000063 \times 10^6$$

$$c = 1.0906 \times 10^9$$

$$d = 1.0822 \times 10^9$$

Circuit Equations

$$ad = a + d + \frac{ad}{c} = 1.0842 \times 10^9$$

$$cd = c + d + \frac{cd}{a} = 1.1823 \times 10^{12} = R_x$$

$$R_{KAD} = \frac{ad \times R_{AD}^*}{ad + R_{AD}} = 0.9908 \times 10^7$$

$$R_S = \frac{R_{KAD} \times R_{BC}^*}{R_x} = 83.80$$

$$\left.\begin{array}{l} R_{AD}^* = 10^7 \text{ ohms} \\ R_{BC}^* = 10^7 \text{ ohms} \\ K = 10^{-14} \end{array}\right\} \text{Bridge parameters for this measurement}$$

Acknowledgment

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