110 Years of Resistance Research at NBS/NIST: Reflecting on the Past - Looking to the Future

Dean Jarrett
August 24, 2011
NCSLI, Washington DC
Outline

- 110 Years in 25 minutes (2 minutes per decade)
- Pre NBS
- NBS/NIST Ohm, Resistors
- 1948 1\textsuperscript{st} Redefinition
- 1960 Calculable Capacitor
- 1990 QHR & 2\textsuperscript{nd} Redefinition
- The Future?
“Uniformity in the currency, weights, and measures of the United States is an object of great importance, and will, I am persuaded, be duly attended to.”

George Washington, State of the Union Address, 1790

...The Congress shall have Power To ...

... and fix the Standard of Weights and Measures;

From the U. S. Constitution
Pre NBS/NIST Events

- 1827: Ohm’s Law
- 1843: Wheatstone (Cu wire standard)
- 1851: Weber (Absolute Ohm)
- 1860: Siemens (Mercury Ohm)
- 1875: Treaty of the Meter (BIPM)
- 1887: PTR
- 1888: Zero TCR alloy
- 1890: Reichsanstalt resistor
- 1894: US adopts international units
- 1899: NPL
- 1901: NBS
NBS/NIST Ohm Timeline

1901 NBS Founded
1907 Rosa
1911 Mercury Ohm
1933 Thomas I
1948 1st Redefinition
1956 Thompson-Lampard
1960
1972 CCC
1980 QHR
1990 2nd Redefinition
1995 High Res
2004 Graphene
1995? New SI
2015?

Reichsanstalt
Mercury
Thomas I
Thomas II
QHR
Graphene
NBS/NIST Resistance Standards and Bridges

- Mercury Ohm
- Reichsanstalt Type
- Rosa Type
- Thomas Type I
- Thomas Type II
- Quantum Hall Resistance
- High Resistance

- Wheatstone Bridge
- Rosa Bridge
- Wenner Bridge
- Hamon Resistors
- DC Current Comparator
- Cryogenic Current Comparator
- Automation
Certificate No. 56/1899
for
the electrical precision resistor No. 1498
of
Otto Wolff, Berlin
(Nominal value 0,000 1 ohm.)

The resistor is made of Manganin sheet metal.

According to the test carried out the value of the resistor
at 25.8 degrees C is 0,000 100 027 ohm
" 20.7 " 0,000 100 017 "
1 ohm equivalent to the resistance of a mercury column
106.3 cm long and with a cross-section of 1 sq. mm at 0° C.

These figures determined by comparison with the wire standards of the Imperial Institute are correct to within 0,000 3 of its value.

From them the temperature coefficient is calculated within the above-mentioned limits at + 0,000 02.

Since the resistor at the temperature specified on it deviates less than ±0.001 of its total from the nominal value, it is provided with the imperial eagle, the certificate number and a lead seal, as well as with a star as a precision resistor.

Charlottenburg, on 18. April 1899.

Physisch-Technische Reichsanstalt
Ubersicht II.
Mercury Ohm 1894-1948

“the unit of resistance is represented by … a column of mercury at the temperature of melting ice, 14.4521 g in mass, of a constant cross sectional area of a length of 106.300 cm.”

Advantages
- Easily purified
- High resistivity
- Low TCR
- Reproducible

Disadvantages
- Difficult experiment (only realized at NBS 1911-1912)
- Limited to 20 ppm
1890 Reichsanstalt Type Resistor PTR

Description
Silk covered manganin wire
Coil Dimensions 4 cm (D) x 6 cm (L)
Silk and shellac insulation
Brass bobbin
Baked at 140 °C for 24 hours
Not sealed

Disadvantages
Humidity effects
Stability
1907 Rosa Type Resistor

Description
- Silk covered manganin wire
- Coil: 3 cm (D) x 7 cm (L)
- Silk and shellac insulation
- Brass bobbin
- Baked at 140 °C for 24 hours
- Sealed in mineral oil

Disadvantages
- Stability
- Thermal time constant
1930 Thomas Type Resistor I

Description
- Bare manganin wire, AWG #16
- Coil dimensions 6 cm (D) x 7 cm (L)
- Silk and shellac insulation
- Double wall construction
- Annealed at 550 °C in a vacuum
- Sealed in dry air

Disadvantages
- Load coefficient
1933 Thomas Type Resistor II

Description

- Bare manganin wire, AWG #12
- Coil dimensions 8 cm (D) x 7 cm (L)
- Silk and shellac insulation
- Double wall construction, holes near top
- Annealed at 550 ºC in a vacuum
- Sealed in dry air

Disadvantages

- Pressure coefficient
- Not rugged
1948: 1st adjustment of NBS ohm

1914-1920: Absolute Ohm Experiments: NPL (1914), PTR (1920)
  Absolute Ohm < International Ohm by ~500 ppm

1936-1939: NBS, NPL, PTR, LCE, ETL confirmed

International Committee recommended abandon the Mercury Ohm and return to Absolute Ohm on Jan 1, 1940

World War II delayed change till Jan 1, 1948

NBS Ohm decreased by 495 ppm to agree with international value: all NBS resistance standards increased by 495 ppm
NBS Ohm Drift (1936-1996)

- Early assumption: mean value of group of resistors assumed constant
- **1936 & 1948** Absolute Ohm Experiments: not precise enough to determine the drift
- **1956**: Thompson and Lampard calculable capacitor
- **1960**: NBS Calculable Capacitor 0.3 ± 2 ppm (1 σ)
- **1974**: 0.82 ± 0.06 ppm (2 σ)
- **1989**: 0.022 ppm (1 σ)
- **1996**: 0.024 ppm (1 σ)

\[
\frac{\bar{C}}{L} = \varepsilon_0 \frac{\ln 2}{\pi} \approx 2 \text{ pF/m}
\]

*A cylindrical cross capacitor*
Calculable Capacitor Realization
NBS/NIST Ohm – Quantized Hall Resistance

\[ R_K = \frac{h}{ie^2} \]
\[ T = 278 \text{ mK} \]
\[ I = 0.255 \mu\text{A} \]

\[ i = 2 \quad (12,906.4 \Omega) \]
\[ i = 3 \quad (6,453.2 \Omega) \]
Quantum Hall Resistance: Brief History

Feb 4-5, 1980: discovered By K. Von Klitzing

Aug 1980: Cage, Field, Dziuba start work at NBS

1985: Nobel Prize awarded

January 1, 1990: QHR redefinition

1991: QHR installed in NIST resistance calibration laboratory

1999: NIST and BIPM QHR comparison
1990: QHR, 2nd adjustment of the NBS/NIST Ohm

- January 1, 1990
- +1.69 ppm
- Drift removed
- $R_H = \frac{h}{e^2} \cdot i$
NIST Present Resistance

- Maintenance and dissemination of the US Ohm based upon quantum Hall resistance standard
- Scaling techniques for standard resistors from 0.01 mΩ to 100 TΩ
- Knowledge dissemination to government, industry
Cryogenic Current Comparator

• 1972 Harvey
• 1974 Sullivan & Dziuba
• 1991 Isolated Ramping Current Sources
• 1992 Resistance Scaling
• 1994 High Temp CCC
• 2003 High Resistance CCC
High Resistance scaling

- Utilizes two-terminal QHE device configuration as standard
- Broadens and simplifies use of cryogenic current comparators
Standard Resistor Development: 1995

Guarded Hamon standards for scaling
- Guarded, hermetically sealed
- Low VC, TC, and Drift
- Verify scaling

Discrete High resistance standards
- Hermetically sealed
- Rugged packaging
- Guarded – Can be used with guarded and unguarded measurement systems
- For CCEM-K2 key comparison, piloted by NIST
SIM Comparison of DC Resistance at 1 Ω, 1 MΩ, and 1 GΩ

6 NMI’s within SIM.
3 decades of resistance.
2 standard at each level.
2 opportunities for each non-pilot NMI.
4 loops, return to pilot after each loop.
Linked to Key Comparison results to support U. S. trade.
Graphene Based Quantum Metrology

Goal: To develop intrinsic quantum electrical standards and innovative quantum devices based on the unique properties of graphene

Thursday @ 9am: Rand Elmquist

“Graphene: Plane and Simple Quantum Metrology?” in Chesapeake DEF
The Future: Other NIST Resistance Projects

DC Current Transformers
20 A, 200 A, 2000 A
NSLS-II, DC trans lines

Low DC Current Source and Measurement with Standard Resistors and Current-to-Voltage Converters

Aerosol Electrometers (20 fA – 40 fA), Photodiode detectors (10 pA – 10 μA), Ionizing Radiation Chambers (1 pA – 200 nA)
Historical Resistance References


NIST publications may be obtained at:

http://www.nist.gov/publication-portal.cfm

Thank you for your attention.