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This is the author's submitted version of the contribution published as:

*Original*

Chasing the ohm / Callegaro, Luca. - In: NATURE ELECTRONICS. - ISSN 2520-1131. - (2026).  
[10.1038/s41928-026-01614-3]

*Availability:*

This version is available at: 11696/89579 since: 2026-05-07T06:25:15Z

*Publisher:*

Nature Publishing Group UK

*Published*

DOI:10.1038/s41928-026-01614-3

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15 May 2026

# Chasing the ohm: a journey from mercury to the quantum realm

Luca Callegaro

Istituto Nazionale di Ricerca Metrologica (INRIM), Strada delle Cacce  
91, Torino, 10135, Italy.

## Abstract

The evolution of the ohm as the unit of electrical resistance mirrors the very progress of physics itself. Its realisation has journeyed from mercury columns to mechanical constructs. It now finds permanence in the quantum Hall effect, where semiconductor devices, and their successors in graphene and topological matter, embody Nature's immutable constants.

## 1 Cgs and international units

What's in a name? For over 150 years the ohm stood as the measurement unit of electric resistance for more than 150 years. What we mean by “a resistance of  $x$  ohm”, however, evolved substantially, both in meaning and in magnitude, over time. The story of such evolution intertwines with breakthroughs in fundamental physics, material science, and electrical engineering.

The first metric system of units that evolved was the *cgs*, centimetre-gram-second. Originally proposed in 1832 by Gauss (in the variant millimetre-milligram-second) it was quickly adopted and recommended in 1873 by the British Association for Advancement of Science (BAAS), the most important scientific body of the time. As the *cgs* name suggests, in the system there is no space for electromagnetic base units. All quantities of electromagnetism are measured in mechanical units, chosen to be consistent with the mechanical manifestations of electromagnetism. Two options were available. The *electrostatic cgs* was based on the Coulomb's force law between charged particles, with resistance measured in  $\text{cm}^{-1}\text{s}$ , or *statohm*); and the *electromagnetic cgs*, which has the Ampère's force between current-carrying conductors as foundation, with the unit  $\text{cm s}^{-1}$ , or *abohm*.

Quantity	electrostatic cgs		electromagnetic cgs	
	Current	statampere	336 pA	abampere
Voltage	statvolt	300 V	abvolt	10 nV
Resistance	statohm	899 GΩ	abohm	1 nΩ
Capacitance	cm	11 pF	abfarad	1 MF
Inductance	—	—	abhenry	1 nH

**Table 1** Some cgs units for electromagnetic quantities. An approximate conversion to the corresponding SI units is also given. The statohm and abohm are related by the huge numerical factor  $c^2 \approx 8.987\,552 \times 10^{20}$ .

A.—Tension.			
1 Daniell's Element	...	...	... = 1 Ohma, or unit of tension.
B.—Quantity.			
1 Ohma, by one metre square at one millimetre distance	...	...	} = 1 Farad or unit of quantity.
C.—Current.			
1 Farad per second	...	...	... = 1 Galvat, or unit of current.
D.—Resistance.			
1 Farad per second	...	...	... = 1 Volt, or unit of resistance.

**Fig. 1** Clark and Bright proposal for the names of four practical electrical units [1]. It is worth noting that Ohma was chosen as the unit of voltage, and Volt as the unit of resistance.

Quantity	international unit	definition (practical realisation)
Current	ampere	The unvarying current which, when passed through a solution of silver nitrate in water, deposits silver at the rate of 0.001 118 00 grams per second
Voltage	volt	$\frac{1000}{1434}$ of the electromotive force of a Clark cell at a temperature of 15 °C
Resistance	ohm	The resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice 14.4521 g in mass, of a constant cross-sectional area and of the length of 106.3 cm

**Table 2** The international units, as established in 1893.

29 Table 1 shows the sizes of some cgs units, and displays how they are unusably large  
30 or small for everyday measurements. A need for *practical* electromagnetic units, that  
31 could be accurately reproduced using standardized procedures and simple devices,  
32 quickly emerged. A first proposal, in 1861 from Clark and Bright [1] (see Fig. 1), intro-  
33 duced the Ohma, Farad, Galvat and Volt—names playfully derived from the founding  
34 fathers of electromagnetism. The nomenclature was accepted by the BAAS in 1874



**Fig. 2** Mercury ohm according to the 1898 German Imperial Law “Concerning Electrical Units of Measurement”, Implementation Regulation for the International Ohm. Museum display of the Physikalisch-Technische Bundesanstalt, courtesy of H. Scherer.

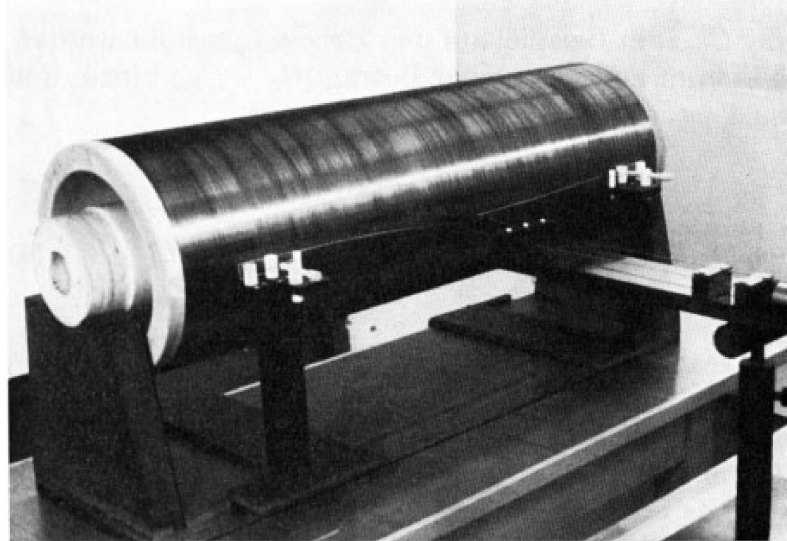
35 (with some rearrangement: the Ohma was shortened to Ohm and assigned to the  
 36 unit of resistance). Such names were made permanent by the International Electrical  
 37 Congress (IEC, now International Electrotechnical Commission) in its meetings of  
 38 1881 and 1893 [3], where the international ohm, together with the international ampere,  
 39 volt, coulomb and farad, were defined as multiples of the corresponding cgs units.

40 The IEC also defined *practical representations* of the units through electrical  
 41 devices [3], as shown in Table 2. The international ohm was defined as the resistance  
 42 of a column of mercury of given weight and length, see Figure 2. Because the resistiv-  
 43 ity of pure metals is highly sensitive to impurity, mercury—the purest available metal,  
 44 thanks to vapour distillation—became the natural choice.

## 45 2 The SI and the absolute realisation of the ohm

46 International units, although designed to be multiples of cgs units, were in fact inde-  
 47 pendent of them. Over time, with the improvement of experimental techniques, the  
 48 conversion factors between absolute and international units started to deviate from the  
 49 intended simple powers of ten. Further, the definition of international units was not  
 50 *coherent*: for a given realisation of all the three units, Ohm’s law is not automatically  
 51 satisfied.

52 The very same experimental improvements made direct, *absolute* realisations more  
 53 feasible over time. As said, electromagnetic units were ultimately mechanical in their  
 54 definition, so mechanical experiments had to be performed. Dozens of possible absolute  
 55 realisations of the ohm were considered [4], based on different principles: electrody-  
 56 namic force, induced voltage in moving coils, calorimetric. . . Among many ingenious  
 57 designs, the *calculable inductor* emerged as the most elegant and accurate, either in  
 58 their mutual or self-inductance (see Figure 3) variants. The measurement of a resistor



**Fig. 3** Calculable inductor. The coil, wound in a single layer on a non-magnetic ceramic core, has 945 turns with a diameter of 310 mm and a length of 709 mm. Adapted from [2].

59 versus the calculable inductor required one or more dedicated ac impedance bridges,  
60 operating at a known frequency. The uncertainty of such absolute realisation was  
61 ultimately related to that of the cumbersome mechanical measurements of the 3D  
62 helical geometry of the inductor, and was pushed down to  $2 \times 10^{-6}$  in the most recent  
63 experiment (1968 [2]).

64 In 1956 a totally unexpected theoretical result in electrostatics—the first since  
65 several decades—opened a new way to realise the farad and the ohm. The *Thompson-*  
66 *Lampard theorem* showed that, for an arrangement of four cylindrical electrodes in a  
67 square, the capacitance per unit length between opposite electrodes had the simple  
68 expression  $C = \epsilon_0 \log 2/\pi = 1.95354904 \dots \text{pF m}^{-1}$ . The value, related to the vacuum  
69 permittivity  $\epsilon_0$  by an exact numerical constant, is robust with respect to deviations  
70 from an ideal symmetric geometry. The measurement of a straight segment length,  
71 performed with optical interferometry, is sufficient to calculate a capacitance value. A  
72 very small value indeed, which can nevertheless be scaled to higher capacitance, and  
73 then to resistance, with the coaxial transformer impedance bridges whose development  
74 flourished in the same years. The uncertainty of the absolute realisation of the ohm  
75 could now be pushed down to parts in  $10^8$ . In 1960 the adoption of the International  
76 System of units, with the choice of the ampere, defined in mechanical terms, as the base  
77 unit, consolidated the need of realisation of the electrical units with electromechanical  
78 experiments, an specifically the ohm with the calculable capacitor.

### 79 3 A mechanical and a quantum ohm, together

80 In the 20th century the ultimately quantum nature of all electromagnetic phenom-  
81 ena was progressively better understood. Nevertheless, the discovery of the quantum  
82 Hall effect, by Klaus von Klitzing in 1980 came as a surprise <sup>1</sup>. Consider a solid-state  
83 device where charge carriers are constrained in a two-dimensional layer, at a suffi-  
84 ciently low temperature and with a static magnetic field applied perpendicularly to  
85 the surface. The Hall resistance, the ratio between the Hall voltage and the current  
86 flowing in the device, becomes quantized. The quantum Hall resistance (QHR) value  
87  $R_H = R_K/i$  is a unit fraction  $1/i$  of the resistance quantum  $R_K = h/e^2 \approx 25\,812\,\Omega$ , a  
88 fundamental constant of nature being a combination of the Planck constant  $h$  and the  
89 elementary charge  $e$ . The robustness of the effect (in proper samples currents in the  
90 tens of microampere range can be applied) allows one to perform measurements to the  
91 highest accuracy. Tests of the *universality* of the quantum Hall resistance, its indepen-  
92 dence of the specific device employed, is established to an accuracy of about ten parts  
93 per trillion ( $10^{-12}$ ). QHR experiments were much easier to perform than the delicate  
94 calculable capacitor experiment, and were installed in most major national metrology  
95 institutes as a representation of the ohm to establish the national resistance standards.

### 96 4 The 1990 conventional ohm

97 The adoption of QHR as a resistance standard raised a problem. It allowed a repre-  
98 sentations of the ohm with a reproducibility two to three orders of magnitude better  
99 than the uncertainty of  $R_K$  in SI ohm—the latter becoming the major limitation  
100 to the development of resistance metrology. A solution was to introduce, in 1990, a  
101 *conventional value*  $R_{K-90} = 25\,812.807\,\Omega$  for the von Klitzing constant, a value cho-  
102 sen to match the best measurements performed in terms of the calculable capacitor.  
103 This conventional value (and the corresponding one for the other quantum metrology  
104 experiment, the Josephson voltage standard) defined a system of *conventional electri-  
105 cal units*:  $\Omega_{90}$ ,  $A_{90}$ ,  $V_{90}$ , etc. All electrical measurements and calibrations since then  
106 were performed in conventional units.

107 A century later, history repeated itself: the 1990 conventional ohm revived the  
108 same problems of the 1893 international ohm. After its introduction further, more  
109 accurate determinations of  $R_K$  were made: the conventional ohm was shown to be no  
110 longer exactly equal to the to the SI ohm. The conventional system of units became,  
111 like the 1893 one, noncoherent.

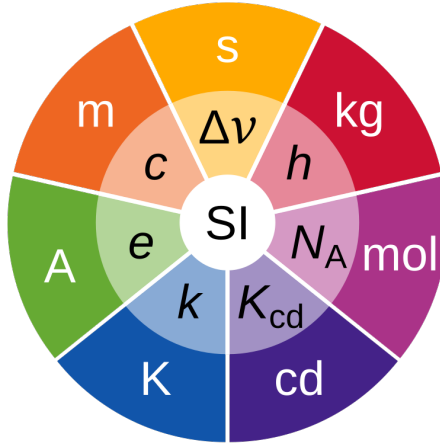
### 112 5 The quantum SI

113 The existence of a parallel system of conventional electrical units, drifting from the  
114 corresponding SI one, was recognized as a major problem of the SI.<sup>2</sup> The need of a  
115 revision was recognized at the turn of this century, and several solutions proposed and  
116 discussed over two decades.

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<sup>1</sup>A detailed history of the discovery of the quantum Hall effect is narrated in excellent recent reviews, e. g. [5], and will not be told again here.

<sup>2</sup>The main problem was the suspected instability of the *International Prototype Kilogram*, which defined the unit of mass.



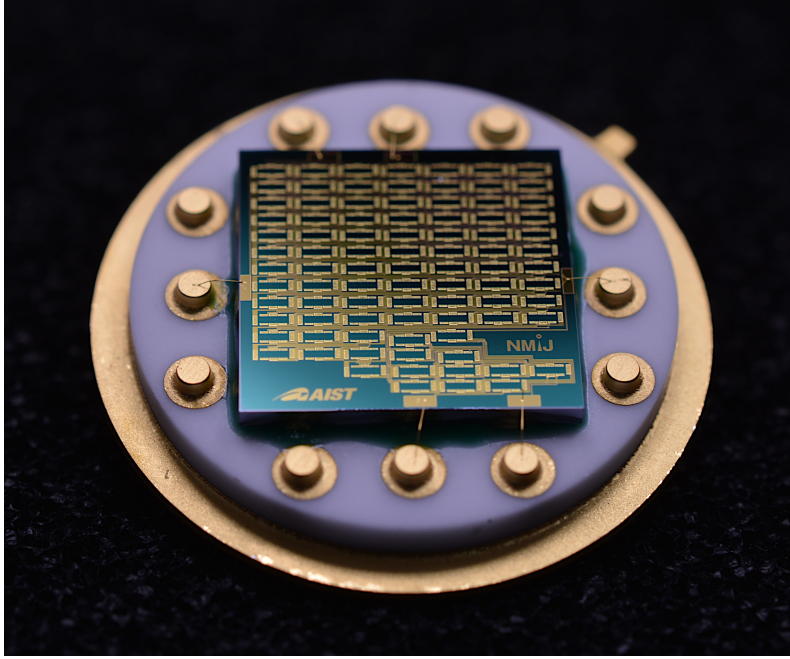
**Fig. 4** A pictorial representation of the SI, highlighting the base units and the fundamental constants that enter their definition.

117 The revision of the SI was approved by the 26th General Conference of Weights and  
 118 Measures in November 2018 [6] and implemented on 20 May 2019, the *implementation*  
 119 *day*. The present SI, see Figure 4, is based on a set of seven constants with exactly  
 120 specified numerical values. The elementary charge  $e$  has the exact value  $1.602\,176\,634 \times$   
 121  $10^{-19}$  C, and the Planck constant  $6.626\,070\,15 \times 10^{-34}$  J s. Consequently, The resistance  
 122 quantum also has the exact value  $R_K = h/e^2 = 25812 \dots \Omega$ . The QHR is a realisation  
 123 of the ohm, and all electromagnetic units can be similarly realised with quantum  
 124 experiments.

## 125 6 New physics for resistance metrology

126 The von Klitzing 1980 experiment was performed on a silicon MOSFET device with  
 127 a current of  $1 \mu\text{A}$ . The applied magnetic field was 18 T at a temperature of 1.5 K. The  
 128 two-dimensional electron transport was forced by the electrostatic field generated by  
 129 a voltage of 23 V applied to the MOSFET gate. The relevance for metrology of the  
 130 original QHR experiment was immediately recognized, and efforts made to find better  
 131 QHE devices that could simplify the implementation of QHR experiments for metrol-  
 132 ogy purposes. A major improvement was the development of GaAs heterostructure  
 133 devices in the 1980s. These devices allow to increase the applied current to tens of  
 134  $\mu\text{A}$ , moderately reduce the magnetic field needed (to around 10 T, in the range of a  
 135 standard superconducting magnet) and do not need a gate voltage. The QHR of GaAs  
 136 devices is presently *the* basis of resistance metrology worldwide.

137 Graphene, the first two-dimensional material, was discovered in 2005. QHR in  
 138 graphene is more robust than in GaAs, and manifests at higher temperature and  
 139 lower magnetic fields. After several years of development it is now possible to access  
 140 QHR in stable devices, at temperatures of several K, by applying a magnetic field of  
 141 5 T or lower, and measurement currents in the  $100 \mu\text{A}$  range [7]. These experimental



**Fig. 5** A GaAs quantum Hall array resistance standard (QHARS). The electrical network of 88 QHE elements gives a  $1\text{ M}\Omega$  output resistance. Courtesy of N.-H. Kaneko, National Metrology Institute of Japan.

142 conditions can be achieved in a tabletop dry cryostat refrigerator, thus providing  
 143 permanent access to the SI ohm with a compact experiment.

144 The quantum of resistance is an invariant given by Nature, luckily in a resistance  
 145 range that is easy to access experimentally and of interest for metrology applications.  
 146 Calibration centers, however, perform calibrations of commercial resistance standards  
 147 and meters at simple decadal values—such as  $1\ \Omega$  or  $10\ \text{k}\Omega$ . These values can be  
 148 obtained by scaling QHR with commercial resistance ratio bridges, but some accuracy  
 149 is lost in the process.

150 QHR devices are fabricated with semiconductor foundry techniques, and integra-  
 151 tion is possible. *Quantum Hall array resistance standards* (QHARS) are integrated  
 152 circuits of several QHR elements that display perfect fractions (either smaller or  
 153 greater than 1) of  $R_K$ . Figure 5 shows an example of a  $1\ \text{M}\Omega$  GaAs QHARS. A recent  
 154 development is a single graphene device which outputs  $100\ \Omega$ ,  $1\ \text{k}\Omega$  and  $10\ \text{k}\Omega$  resis-  
 155 tance values, suitable for performing calibration of artifact standards with commercial  
 156 room-temperature resistance bridges [8].

157 Electrical metrologists envision a future where all quantum standards converge to  
 158 became a single *quantum multimeter*. An integration of QHR with the other quantum  
 159 effects (Josephson voltage in particular) in a single environment, possibly based on a  
 160 single chip, to be the basis of an instrument that can measure voltage and current in  
 161 the dc and ac regime, resistance and impedance, directly traceable to the quantum

162 SI units. Several steps are being made, in particular on the exploitation of quantum  
163 devices in the ac regime. However, the high magnetic field required by QHR—fatal  
164 to the Josephson effect, which dies already at very small magnetic fields—remains a  
165 formidable obstacle.

166 A quantized resistance is not exclusive of the QHR. It is related to electron  
167 transport without scattering and manifests in other systems, such as quantum point  
168 contacts. Stable quantized resistance values have been observed, at room temperature  
169 and without applied magnetic field, in *memristors* [9], which also offer resistance pro-  
170 gramming capabilities. The quantization accuracy is presently insufficient to consider  
171 these devices a viable alternative to QHR.

172 A recent breakthrough is given by the *quantum anomalous Hall effect* (QAHE)  
173 in magnetically-doped topological insulator materials. The devices, after an initial  
174 magnetisation cycle, display QHR even at zero magnetic field. A very recent experi-  
175 ment [10] shows the universality of QHE in these devices with an accuracy in the  $10^{-9}$   
176 range. A quantum current generator proof of principle, based on a QAHE device and  
177 on a Josephson voltage array hosted in the same cryostat, has been published [11].  
178 Presently, the drawbacks of QAHE devices are the need of a very low (100 mK or  
179 below) temperature, and very low measurement currents (in the 100 nA range). Ongo-  
180 ing research into these materials, which have many applications, fuels the metrologist's  
181 optimism that today's limitations in the QAHE exploitation will be overcome in the  
182 near future.

183 **Acknowledgements.** The author is indebted with Hansjörg Scherer, Physikalisch-  
184 Technische Bundesanstalt, for providing Figure 2, and Nobu-Hisa Kaneko, National  
185 Metrology Institute of Japan, for Figure 5. Partial funding was provided by the  
186 project 23FUN07 QuAHMET *Quantum anomalous Hall effect materials and devices*  
187 *for metrology*. The project has received funding from the European Partnership on  
188 Metrology, co-financed from the European Union's Horizon Europe Research and  
189 Innovation Programme and by the Participating States.

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