THE ELECTRICAL RESISTANCE OF GOLD AND SILVER AT LOW TEMPERATURES

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Summary

In accordance with the earlier measurements [1]) the resistance curves of the gold wires measured show a minimum. The "ideal" resistance calculated by means of Matthiessen's rule, without taking into account the points below the temperature of the minimum, grows proportionally to $T^{4.2}$. The minimum shifts to higher temperatures, when the residual resistance grows.

One of the samples of pure silver shows a minimum too. The "ideal" resistance, calculated in the same way as for gold, grows proportionally to $T^{4.1}$.

§ 1. *Introduction.* The measurements on platinum [2]), gold [1]) copper [1]), lead [1]), cadmium [3]), thallium [3]) and tin [3]) executed in the Kamerlingh Onnes Laboratory, have been followed by the measurements of the electrical resistance of silver between 1°K and 20°K. The influence of the purity of the metal on the minimum in the resistance-temperature curve of gold has been investigated for different wires.

§ 2. *Description of the experiments.* The electrical resistance has been measured with a Diesselhorst compensation apparatus by comparing the potential differences between both ends of the resistance and of a standard resistance. The temperature range can be divided into three parts:

1°. the temperature range of liquid hydrogen (14.2°K–20.4°K), the temperature being measured with a platinum thermometer;

2°. the temperature range between 4.2°K and 14.2°K. These temperatures were obtained by desorption of helium gas, adsorbed on charcoal [4]). In this way one can have the temperatures from 4.0°K to 15°K, so that an overlapping of the three intervals can be obtained and the points measured in different cryostats can be compared. From 4.0°K the temperature in the desorption apparatus ("Simon"apparatus) rises at a maximal rate of 0.01 degree/min. This rate can be diminished to 0.001 degree/min for about 15 minutes by admitting small quantities of helium gas, which are adsorbed by the charcoal.

The temperature is measured by a calibrated heliumgas-thermometer. A current wire of the resistance is fixed to the thermometer reservoir to make the temperature of the wire equal to that of the thermometer;

3°. the measurements below 4.2°K have been made in a cryostat filled with liquid helium. The temperatures have been determined from the vapour pressure of the liquid.

The measurements at 0°C have been made in a tube filled with petroleum ether, placed in a mixture of distilled ice and distilled water.

§ 3. *Gold.* The material used was obtained from W. C. Heraeus (impurity < 10^{4-} %, traces Cu and Ag [1])), from Adam Hilger Ltd. (Lab. No. 9874, impurity < 10^{-3} %, trace of Ag) and from the "Mint" (impurities Fe and Si).

There were made one resistance from Heraeus gold (Au_{7a}), two resistances from Hilger gold (Au_5 and Au_{6a}) and one resistance from Mint gold (Au_3).

The wires were spiralized and suspended quite freely by the current- and potential wires in a quartz mounting.

All wires were annealed in vacuum by a current going through them.

	Tempering time	Temperature	$R_{0°C}$
Au_1	5.0 h	480°C	1.93593 Ω [1])
Au_2	5.0 h	480°C	0.26426 Ω [1])
Au_3	1.5 h	480°C	0.43293 Ω
Au_5	0.5 h	∽ 500°C	0.40313 Ω
Au_{6a}	3.0 h	∽ 500°C	0.50136 Ω
Au_{7a}	2.5 h	∽ 500°C	0.35383 Ω

Au_{7a} was made from the same gold as Au_1 and Au_2. The annealing time is one half of the annealing time of Au_1 and the residual resistance z ($z = R/R_0$ for 0°K) differs bij 2×10^{-4} or 8 % from the z of Au_1 (see table I and I*a*).

TABLE I (Au 1)

	T °K	$\frac{R}{R_0} \times 10^4$	$z \times 10^4$	$\left[\frac{R}{R_0}\right] \times 10^4$
H*)	20.44	90.48	26.30	64.35
,,	18.08	65.73		39.53
,,	17.03	57.30		31.08
,,	16.05	50.76		24.52
,,	15.17	45.64		19.39
S	12.10	33.86		7.58
,,	11.95	33.48		7.20
,,	11.84	33.20		6.92
,,	10.00	29.67		3.38
,,	9.95	29.59		3.30
HS	9.38	28.90		2.61
S	8.83	28.26		1.97
,,	7.28	27.14		0.84
,,	6.54	26.85		0.55
,,	6.08	26.74		0.44
,,	4.81	26.51		
He	4.23	26.44[5]		
,,	3.77	26.44		
,,	3.12	26.46		
,,	2.39	26.52		
,,	1.63	26.66		

*) H = measurements in liquid hydrogen.
He = measurements in liquid helium.
S = measurements in the "Simon" apparatus.
HS = measurements in the "Simon" apparatus surrounded by liquid hydrogen.

TABLE Ia (Au 7*a*)

	T °K	$\frac{R}{R_0} \times 10^4$
H	20.46	95.53
,,	19.09	79.76
,,	18.12	70.43
,,	16.96	60.68
,,	15.96	53.64
,,	14.33	44.74
He	4.30	29.01
,,	3.86	28.91
,,	2.98	28.97
,,	2.03	29.08
,,	1.26	29.31

TABLE II (Au 5)

	T °K	$\frac{R}{R_0} \times 10^4$	$z \times 10^4$	$\left[\frac{R}{R_0}\right] \times 10^4$
H	20.46	170.73	100.50	70.94
,,	19.13	154.79		54.84
,,	19.08	154.48		54.53
,,	18.10	144.39		44.34
,,	17.16	135.99		35.85
,,	16.96	134.50		34.35
,,	15.95	126.90		26.67
,,	14.33	117.20		16.87
,,	14.12	116.09		15.75
H.S	9.56	102.94		2.46
S	6.25	100.95		0.45
,,	5.97	100.95		
,,	5.67	100.97		
,,	5.15	101.08		
,,	4.98	101.14		
He	4.30	101.35		
,,	2.97	102.35		
,,	2.03	103.58		
,,	1.26	105.37		

TABLE III (Au 6*a*)

	T °K	$\frac{R}{R_0} \times 10^4$	$z \times 10^4$	$\left[\frac{R}{R_0}\right] \times 10^4$
H	20.46	158.11	88.72	70.04
,,	19.08	142.00		53.77
,,	18.13	132.30		43.99
,,	16.96	122.12		33.70
,,	15.96	114.63		26.13
H.S	15.17	110.55		22.03
H	14.33	105.10		16.55
H.S	13.88	103.97		15.37
,,	10.92	93.67		4.99
,,	9.39	91.05		2.37
,,	9.35	90.98		2.28
S	8.03	89.97		1.26
,,	7.30	89.62		0.91
,,	7.20	89.58		0.87
,,	6.60	89.46		
,,	5.60	89.46		
,,	4.66	89.70		
He	4.30	89.59		
S	4.05	89.92		
He	2.97	90.57		
,,	2.03	91.80		
,,	1.26	93.58		

The annealing times of Au_5 and Au_{6a} have a difference of 2.5^h. and the residual resistances z also differ by 12×10^{-4} or 13% of the z of Au_{6a} (table II and III).

All resistance temperature curves show a minimum (see fig. 1 and 2 and table IV).

TABLE IV (Au_3)

	T °K	$\frac{R}{R_0} \times 10^4$	$z \times 10^4$	$\left[\frac{R}{R_0}\right] \times 10^4$
H	20.47	295.98	220.07	77.62
,,	18.44	271.45		52.54
,,	17.14	258.47		39.26
,,	16.10	249.00		29.58
,,	14.17	237.32		17.64
S	10.88	224.98		5.02
H.S	9.34	222.48		2.46
S	9.21	222.35		2.33
S	8.89	221.93		1.90
,,	8.39	221.59		1.55
,,	7.93	221.32		1.28
,,	6.50	221.19		
,,	5.90	221.30		
,,	5.37	221.50		
,,	4.92	221.74		
He and S	4.30	222.28		
S	4.00	222.47		
He	3.69	222.80		
,,	3.58	222.98		
,,	3.09	223.63		
,,	2.09	225.67		
,,	1.72	226.76		
,,	1.48	227.74		

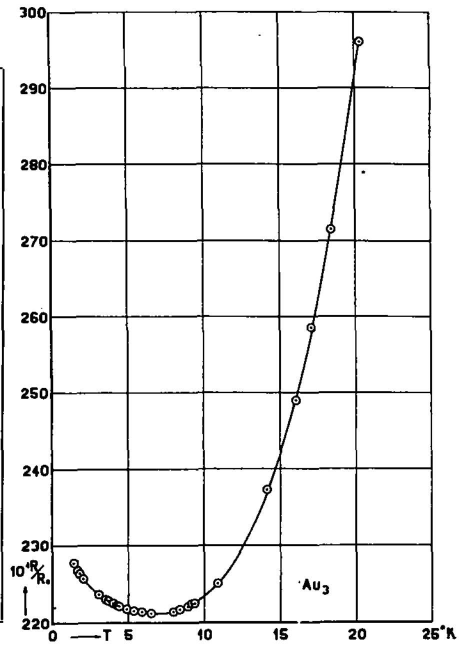

Fig. 1. Electrical resistance of Au_3.

The minimum shifts to lower temperatures when the residual resistance gets smaller.

	Temperature of the minimum	$\frac{R}{R_0}$ of the minimum
Au_3	6.95°K	221.1×10^{-4}
Au_5	6.15°K	100.9×10^{-4}
Au_{6a}	5.95°K	89.40×10^{-4}
Au_{7a}	3.80°K	28.86×10^{-4}
Au_1	3.70°K	26.57×10^{-4}

The question arises, whether this minimum is connected with the minimum, found in the heat resistance curves of pure metals. In order to settle this a special set of measurements is now in preparation.

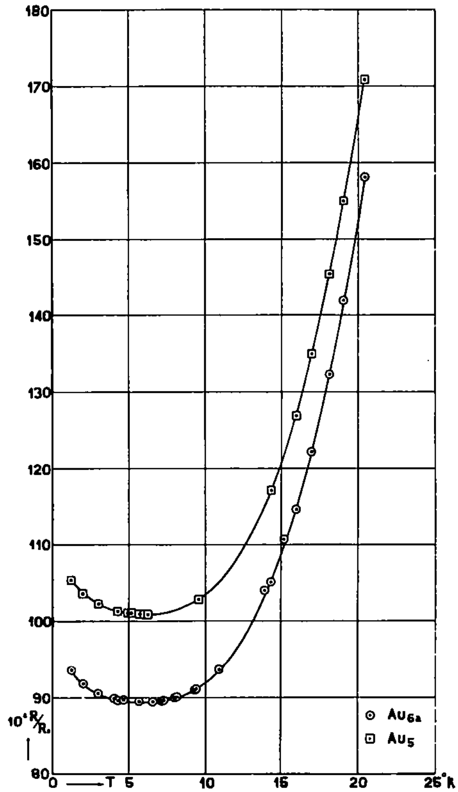

Fig. 2. Electrical resistance of Au_5 and Au_{6a}.

The temperature of the minimum as a function of the R/R_0 of the minimum forms a smooth curve (see fig. 3).

Extrapolation of this curve seems to indicate that $(R/R_0)_{min.} = 0$ at 0°K.

The temperature of the minimum for the purest gold with a residual resistance 0.00029, measured by Meissner [7]), can be found from the extrapolated curve and is 1.35°K. This is the lowest temperature of the points of Meissner. Hence he should have found no minimum — a prediction which agrees with his result.

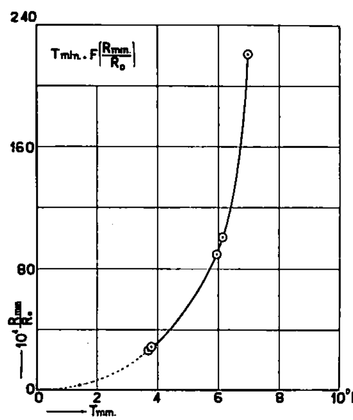

Fig. 3. $T_{min.}$ as a function of $(R/R_0)_{min.}$

The "ideal" resistance of the different gold wires calculated by means of Matthiessen's rule [5]) after extrapolating the resistance curve from the minimum to 0°K, is representable by the formula:

$$\left[\frac{R}{R_0}\right] = AT^B,$$

B having the value 4.2 (see fig. 4).

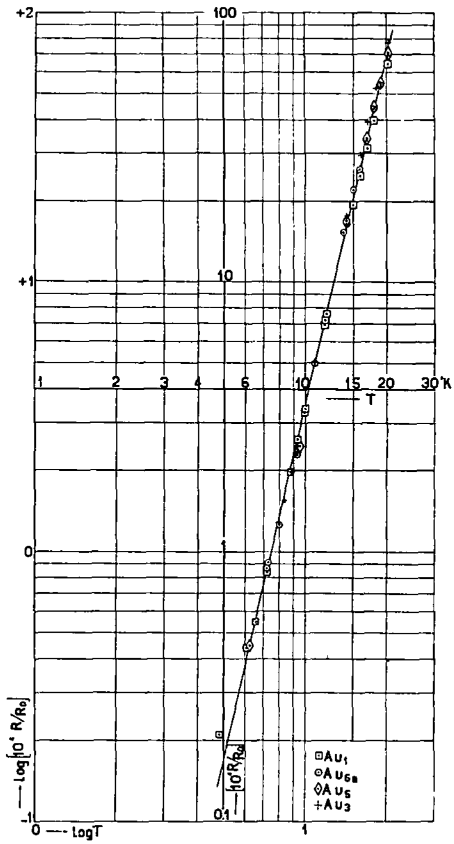

Fig. 4. "Ideal" electrical resistance of gold.

This points to the formula of Grüneisen [6]), where $B = 4{,}0$.

§ 4. *Silver.* The metal was obtained from Adam Hilger Ltd. (Lab. No. 5939) in rods of 7 mm diameter.

A piece of such a rod was melted and pressed in a quartz tube of diameter 2 mm. The quartz tube removed, the rod of 2 mm was drawn through agate dyes to a diameter of 0.06 mm.

From this wire were made Ag_1 and Ag_2 (spiralized wires) and Ag_3 (not spiralized). All three wires were suspended freely in the way described above.

The annealing time for the wires is different.

	Annealing time and -temperature		$R_{0°C}$
Ag_1	2 hours	480—500°C	0.88173 Ω
Ag_2	2 hours and 2 hours *)	„	1.13645 Ω
Ag_3	3 hours	„	0.18412 Ω

Ag_3 shows a minimum in the resistance-temperature curve (see table V and fig. 5).

The points in the liquid helium range of Ag_2 (see table VI) are not accurate enough to determine the minimum.

Ag_1 has not a minimum (see table VII and fig. 6).

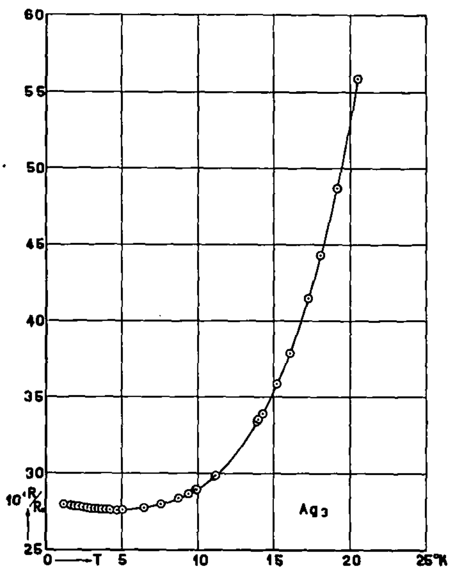

Fig. 5. Electrical resistance of Ag_3.

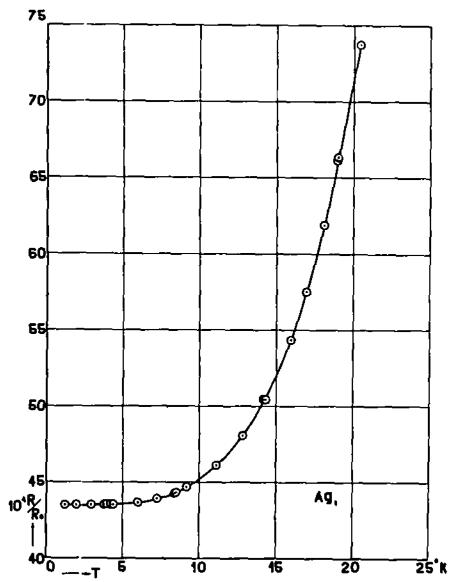

Fig. 6. Electrical resistance of Ag_1.

*) After the first two hours, the wire was not quite free. It was hung in the original form and annealed again for two hours.

The sample shows a residual resistance z higher than that of the other ones. The wire was made of the same silver and treated in the same way as Ag_3 and Ag_2. The annealing times do not differ enough to explain this effect. A shock of the spiralized wire may be the reason for the deviation, but the absence of a minimum still remains incomprehensible.

TABLE V (Ag 3)

	T °K	$\frac{R}{R_0} \times 10^4$	$z \times 10^4$	$\left[\frac{R}{R_0}\right] \times 10^4$
H	20.51	55.82	27.47	28.43
"	19.12	48.68		21.27
"	18.06	44.30		16.88
"	17.25	41.45		14.02
"	16.09	37.86		10.42
H.S	15.19	35.87		8.42
H	14.28	33.84		6.39
H.S	13.97	33.51		6.06
"	13.90	33.39		5.94
"	13.86	33.28		5.83
"	11.15	29.81		2.35
"	11.12	29.18		2.32
"	9.94	28.91		1.44
"	9.88	28.89		1.42
"	9.44	28.68		1.21
"	9.40	28.64		1.17
S	8.76	28.32		0.85
"	7.64	27.95		0.48
"	7.61	27.93		0.46
"	6.53	27.74		0.27
"	6.49	27.71		0.24
"	5.09	27.59		0.10
"	4.71	27.57		
He	4.29	27.57		
S	4.00	27.57		
He	3.73	27.59		
"	3.61	27.62		
"	3.50	27.63		
"	3.38	27.65		
"	3.30	27.67		
"	2.99	27.69		
"	2.51	27.74		
"	2.19	27.78		
"	1.96	27.81		
"	1.72	27.85		
"	1.23	27.91		

TABLE VI (Ag 2)

	T °K	$\frac{R}{R_0} \times 10^4$	$z \times 10^4$	$\left[\frac{R}{R_0}\right] \times 10^4$
H	20.46	54.31	26.59	27.79
"	19.10	47.32		20.79
"	18.12	43.31		16.76
"	16.95	39.26		12.70
"	15.94	36.41		9.85
"	14.31	32.84		6.27
S	10.80	28.76		2.18
"	10.38	28.46		1.88
"	9.82	28.13		1.54
"	9.76	28.08		1.49
H.S	9.26	27.82		1.23
S	8.48	27.46		0.87
"	8.41	27.43		0.84
"	7.40	27.11		0.52
"	7.37	27.08		0.49
"	6.50	26.89		0.30
"	6.48	26.87		0.28
"	6.07	26.81		0.22
"	6.01	26.80		0.21
"	5.50	26.72		0.13
"	5.33	26.71		0.12
"	4.99	26.68		0.09
"	4.50	26.64		0.05
"	4.44	26.63		
"	4.18	26.62		
"	4.14	26.61		
"	4.10	26.62		

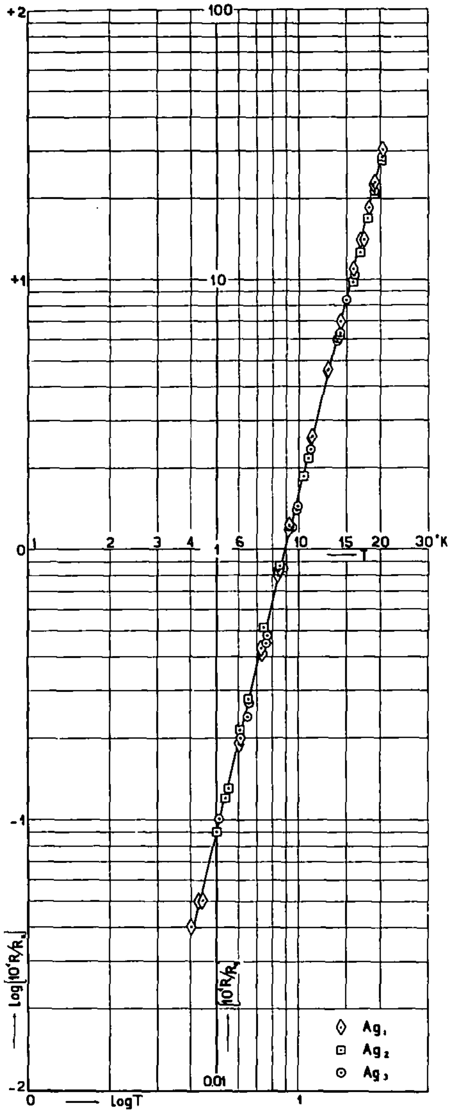

Fig. 7. "Ideal" electrical resistance of silver.

TABLE VII (Ag 1)

	T °K	$\frac{R}{R_0} \times 10^4$	$z \times 10^4$	$\left[\frac{R}{R_0}\right] \times 10^4$
H	20.44	73.72	43.51	30.34
,,	19.06	66.32		22.91
,,	18.98	66.16		22.75
,,	18.12	61.92		18.49
,,	16.96	57.50		14.05
,,	15.96	54.38		10.92
,,	14.36	50.48		7.00
H.S	14.21	50.50		7.02
,,	12.86	48.13		4.64
,,	12.84	48.10		4.61
,,	11.18	46.11		2.61
,,	9.21	44.73		1.23
S	9.19	44.68		1.18
,,	8.49	44.35		0.84
,,	8.40	44.32		0.81
,,	7.31	43.92		0.41
,,	6.09	43.71		0.20
,,	6.02	43.70		0.19
,,	4.41	43.56		0.05
He	4.29	43.56		
S	4.01	43.55		
He	3.86	43.52		
,,	2.97	43.52		
,,	2.02	43.51		
,,	1.26	43.51		

The "ideal" resistance was calculated in the same way as for gold. The three different resistances give a straight line on the logarithmic scale (see fig. 7), so that the "ideal" resistance can be represented by the formula:

$$\left[\frac{R}{R_0}\right] = AT^B,$$

B having the value 4.1.

The investigation of the minima of these two metals is being continued.

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