The Handbook of Electrical Resistivity

New materials and pressure effects

Edited by
G. Dyos

The Handbook of Electrical Resistivity

Other volumes in this series:

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The Institution of Engineering and Technology

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Preface

Since the publication of the *Electrical Resistivity Handbook* by the IET, edited by G.T. Dyos and T. Farrell in 1992, interest in high-temperature superconductivity has grown. I was approached and commissioned by the Institution of Engineering and Technology to produce a further volume covering the electrical resistivity of new materials produced in the last two decades and the effects of pressure on resistivity.

I would be pleased to receive any copies of original referenced papers describing the resistivity of materials which might be of interest for inclusion in a further volume at a later date.

I would like to thank my wife Muriel who has supported me during this project, often only seeing me when I emerged from the study at mealtimes. Also I would like to thank Professor J. Lawton for his support and helpful discussions and IET staff for sorting out problems in the INSPEC searches.

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Chapter 1

Introduction

G. Dyos and T. Farrell

1.1 Continuation of the *Electrical Resistivity Handbook*

This volume incorporates two sections dealing with the resistivity of elements, compounds and alloys as a function of temperature and pressure and a third section dealing mainly with the resistance of various materials.

The compilation of this volume was made easier by the search facilities of the IET's INSPEC database containing some 13 million papers. From which the leading authors of approximately 3000 papers were contacted by email and postal services. It was very disappointing that only 35% bothered to reply and some 30 authors wanted a free copy of the book! It was very much appreciated by the editor for the plaudits received from university professors for undertaking this work.

1.2 Explanation of the graphical format

The vast majority of the data presented here has been gathered from technical papers published in the last two decades. Some graphical data, which were included in the *Electrical Resistivity Handbook*, have been included in this volume, where they cover a larger temperature range.

The data has been obtained from copies of the pertinent paper, either in graphical or in tabular format. In the case of the graphical format, the graphs have been scanned into the computer and the axes calibrated and the data coordinates used to produce a graph based on a standard graphical format. The resistivity data is expressed in units of ohm metre (ohm m) $\times 10^{-8}$, temperature in kelvin (K), pressure in gigapascals (GPa) and resistance in ohms.

1.3 Material classification

The catalogue system used in this volume is the same as that used in the *Electrical Resistivity Handbook*. First, the materials are listed in alphabetical order. Where

a compound has several elements they are listed in order of decreasing atomic percentage. Should a compound have elements all having equal atomic percentage, then they are listed in alphabetical order.

Data which has been presented in the original paper in graphical form and then extracted by scanning and replotting is indicated by an asterisk (*) against the reference number for that graph. It should be noted that only data obtained from bulk and crystalline materials has been evaluated. No data from thin films has been used.

It should be noted that the majority of authors of papers do not indicate whether an allowance for thermal expansion has been applied to the resistivity of the compound.

All the compounds in this handbook are expressed in terms of atomic percentages, that is, the number of atoms of an element present in the compound expressed as a percentage of the total number of atoms present in one molecule of the compound. Where compounds have been listed in the original reference as weight percentages, these have been converted into atomic percentages.

1.4   Electronic conduction in solids

To aid the understanding of the electrical resistivity data on the materials presented in this handbook and to assist with its estimation for materials whose exact composition is not listed, some fundamental concepts of electronic conduction in solids are required. These concepts are presented at the descriptive level; the reader who requires a more detailed quantitative approach should consult the standard text books [1–5] or the cited references.

Electronic conduction is concerned with the motion of electrons within the solid under the influence of an applied electric field. Of necessity, therefore, the electrons must be free to move; experience shows that metals are good conductors of electricity and thus some of the electrons in the metal can be regarded as 'free'. The earliest approach to quantifying the electrical conduction in metals, recognising that electrons were responsible for the transport of charge, was that of Drude [6], who treated the metal as an electron gas. When an electric field, E, is applied to the metal, the electrons of charge $-e$ are accelerated by the electrostatic force eE. After they have travelled for a certain average time, τ, the electrons suffer a collision with the atoms of the solid and are effectively arrested, transferring their kinetic energy to the solid. From simple mechanics, the mean drift velocity of the electrons, v_D, is given by

$$v_D = \frac{Ee\tau}{m}$$

where m is the mass of the electron. If the volume density of the electrons is n, then the electrical current per unit area, J, is given by

$$J = nev_D = \frac{ne^2\tau E}{m} \tag{1.1}$$

This is a statement of Ohm's law, where the electrical conductivity ρ is defined as $J = \sigma E$.

The electrical resistivity $\rho = 1/\sigma$ is therefore

$$\rho = \frac{m}{ne^2\tau} \tag{1.2}$$

To obtain an estimate of ρ from (1.2), the values of n and τ are required. Taking the 'relaxation time' τ to be given by λ/v_0, where λ is the electron mean free path and v_0 the thermal velocity of the electrons, then from the equipartition law $mv_0^2/2 = 3k_BT/2$ and

$$\rho = \frac{(3k_BmT)^{1/2}}{n\lambda e^2} \tag{1.3}$$

If it is assumed that each atom contributes one electron to the conduction process, n is the number density of atoms in the solid, and if λ is taken to be the interatomic spacing, then (1.3) gives values of ρ in the 10^{-6} to 10^{-7} ohm m range, which covers the room temperature experimentally observed resistivities for most metals.

Although this simple classical Drude theory gives Ohm's law and taking the power dissipation to be approximately mv_D^2/τ is consistent with Joule heating (it can also be used to derive the relationship between the electrical and thermal conductivities of metals – the Wiedemann–Franz law), it cannot readily explain the differences in the electrical resistivity upon alloying, nor does it predict the correct variation of resistivity with temperature. The Drude theory is restricted to metals; it cannot explain the electrical resistivity of semiconductors. However, the important point to emerge from this approach is the concept of collisions or scattering of electrons and the significance of τ, the 'relaxation time'.

The quantum mechanics approach pioneered by Sommerfeld [7] assumes the free electrons of the metal to be moving in a constant internal potential and that the electrons in this potential well obey the laws of quantum mechanics rather than the laws of classical mechanics. Essentially, this well consists of a quasi-continuum of energy levels and when the valence electrons are 'poured' into the well they progressively fill these levels up to a certain energy, E_F, known as the Fermi level. This value of E_F varies from metal to metal but is typically a few electron volts (1 eV $= 1.6 \times 10^{-19}$ J). In this quantum Fermi gas model, the number of electrons which take part in the conduction is restricted to those lying within the energy range k_BT of the Fermi level, where k_B is Boltzmann's constant. Thus, at room temperature, for a monovalent metal with $E_F \approx 5$ eV, the number of electrons is only 5×10^{-3} times the total number of valence electrons. The average drift velocity of the classical mechanics is replaced by the Fermi velocity, $v_F \approx (2E_F/m)^{1/2}$, which for $E_F \approx 5$ eV is about 1.3×10^6 m/s. If these mean values are substituted into (1.3), and the mean free path, λ, is again taken to be the interatomic spacing, then the Sommerfeld model predicts a resistivity which is several orders of magnitude larger than the experimental values. However, the Fermi gas model derives the Wiedemann–Franz law with remarkable agreement with experiment and successfully accounts for electronic specific heat. Thus, the difficulty it encounters in describing conductivity must lie in the

definition of the mean free path. In order to reconcile the prediction of the Fermi gas model with experiment, the electron mean free path must be larger than interatomic spacings.

The Fermi gas model, in its simplicity, treated the electrons as being in a constant potential well. Solids are comprised of crystals, the sizes of which are large compared with atomic dimensions (with the exception of amorphous metals). Each ion within the crystal lattice has its own potential well, and as the ions are arranged periodically, there is a periodic arrangement of potential wells.

If one atomic potential well is considered in isolation, then there are discrete electron energy levels such as those that are encountered in the hydrogen atom. If two such wells are brought into close proximity, then from the Pauli exclusion principle which forbids any two electrons from occupying the same energy level (neglecting electron spin), the isolated discrete energy levels split into two levels. When a large number, N, of such wells are brought into close proximity, which is the case in a crystal lattice, then the original discrete energy level is broadened into a quasi-continuous energy band (actually comprising N energy levels). The gaps between the original isolated discrete energy levels may be preserved, but are smaller; in some cases the gaps no longer exist and the energy bands overlap. This 'Band Theory of Solids' provides the framework for understanding the classification of solids into metals, semiconductors and insulators.

If the electron is considered to be a wave travelling perpendicular to a set of lattice planes, then Bragg reflection will occur at certain wavelengths. For these wavelengths, λ_F, the wave is not propagated through the crystal and therefore they are forbidden to the conduction electrons of the crystal. The wave vectors, k, corresponding to the wavelengths ($k = 2\pi/\lambda_F$) occur at the boundaries of the Brillouin zone (the unit cell of the reciprocal lattice) and constitute energy gaps.

The Brillouin zone model relates the electron energy levels to the crystal structure. In regions close to the zone boundaries the variation of electron energy with its wave vector deviates from that where the periodic potential can be treated as constant, as a direct result of energy gaps. One consequence is that the mass of the electron is no longer that of the free electron; if the Fermi level occurs in such a region, the mass of the electron should be replaced by an effective mass, m^*, and this can be quite different from m.

The quantum mechanical approach provides the basis for the understanding of solids in terms of their conduction behaviour. The band theory and Brillouin zone model are primarily concerned with electronic structure, whereas electron conduction is concerned with the motion of the electrons under the influence of an externally applied electric field within that structure. The solution to the vexing problem of the mean free path being considerably larger than atomic dimensions was provided by Bloch [8], who considered, via a Fourier analysis, the propagation of electron waves in the lattice structure. If the structure is perfectly periodic, no scattering occurs, whereas deviations from periodicity give rise to scattering and hence to electrical resistance.

If the potential wells at the lattice sites are identical and the lattice sites themselves are regularly spaced, then the electron wave propagates almost undisturbed; in other words, very little scattering occurs, which is equivalent to a mean free path

which is much longer than interatomic distances. In fact, in a perfectly periodic structure, the electron wave is not disturbed at all and in such a structure the resistivity would be zero (this is not to be confused with superconductivity, where the resistivity is zero in non-periodic structures). A perfectly periodic structure is never realised in practice although it is approached in very pure single crystal solids at temperatures close to absolute zero.

Thus, in normal solid electronic conductors, the electrical resistivity arises from departures from periodicity in the lattice potential wells and there are many ways in which this can occur. These include

(i)   displacement of the atoms due to their thermal motion;
(ii)   imperfections in the crystal lattice, such as dislocations, vacancies and grain boundaries in polycrystalline solids;
(iii)   the substitution of foreign atoms at the lattice sites.

The departures from periodicity arising from (i) and (ii) are characteristic of pure metals whilst all three sources contribute to the resistivity of metallic alloys.

1.5   Pure metals

In a well-annealed pure metal at low temperature, the density of the imperfections is low and their contribution to the electrical resistivity is small. Dislocations, which arise for example by cold working, give rise to a temperature-independent resistivity which is usually negligible in comparison with the resistivity at high temperatures where phonon scattering dominates (see below) but may contribute significantly to the resistivity at cryogenic temperatures. For this reason, when studying pure metals it is preferable to use well-annealed specimens. On the other hand, vacancies are thermally activated; their number density increases with temperature. At room and cryogenic temperatures, the vacancy contribution to the resistivity is negligibly small and only starts to become significant at temperatures approaching the melting point. However, this is somewhat academic in the sense that the vacancy contribution to the resistivity is inherent to the metal and temperature.

At finite temperatures, the atoms vibrate about their mean positions. Effectively, the interatomic spacing is no longer constant; as the temperature increases, so does the amplitude of the vibrations, giving rise to greater changes in the interatomic spacing and hence larger departures from periodicity. The result is a temperature variation of the mean free path and hence of the electrical resistivity.

The vibration of the atoms can be regarded as waves propagating through the crystal lattice. By treating the lattice vibrations as being quantised (the quantum of energy is known as a phonon), it can be shown that there is a cut-off phonon frequency; phonons of frequency larger than the cut-off frequency are not allowed. The temperature corresponding to this frequency is known as the Debye temperature (usually denoted by θ_D).

Now the scattering of the electrons is essentially the interaction of the electron waves (which are defined by the periodicity of the lattice) and the displacements of

the lattice sites which can be described by lattice waves. The characteristic electron energy E_F (the Fermi energy) is equivalent to many thousands of degrees kelvin, whilst the Debye temperature is typically a few hundred degrees kelvin. Thus, the effect of temperature on the electronic structure of a solid is small compared with its effect on the lattice and, consequently, for scattering purposes, the effect of temperature on the lattice only need be considered.

At temperatures above θ_D, all lattice modes are excited and contribute to the scattering of the electrons. The phonon occupancy of the excited lattice modes increases linearly with temperature and consequently, as the mean free path is inversely proportional to the number of scattering centres, the resistivity increases linearly with temperature. At temperatures much lower than θ_D not all lattice modes are excited; only those with frequency v less than $k_B T/h$ (where h is Planck's constant) will be excited, and at very low temperatures the number of excited modes falls off as $(T/\theta_D)^3$. Thus, for temperatures lower than θ_D, the resistivity varies more rapidly than linear, and it was shown by Bloch [9] that at these very low temperatures the resistivity varies as the fifth power of temperature. Gruneisen [10] later developed the Bloch analysis to give an expression for the resistivity which covered the entire temperature range.

Some pure metals can exist with different crystal structures known as allotropes. Each allotrope has its own Brillouin zone and thus its own characteristic resistivity, which may exhibit a different temperature dependence. Such phase changes are more often encountered in metallic alloys and these are discussed later.

Whilst electron scattering by phonons is the dominant process in determining the temperature variation of the resistivity of most metals, other temperature-dependent scattering processes, such as electron–electron scattering, which gives a T^2 dependence for the resistivity at low temperatures, occur, and these are often seen in the magnetic and transition metals. Magnetic phase transformations occur in the ferromagnetic metals at the Curie temperature, T_c. These transitions are associated with a continuous decay in long-range magnetic order, which vanishes at T_c. As the temperature is increased and T_c is approached, the resistivity rises at an increased rate reflecting the increase in disorder. At T_c, where magnetic disorder is complete, there is a change in slope of the resistivity/temperature curve.

The abrupt increase in the electrical resistivity of many metals at the melting point in passing from the solid to the liquid state, and its steady increase with temperature in the liquid state, is associated with the absence of long-range crystal structure and the increase in disorder in the liquid state.

1.6   Metallic alloys

1.6.1   Dilute alloys

When a 'foreign' atom is substituted for an atom of the host metal, the potential well at the substitution site is changed. The contributions to the change in the potential well due to the substitution arise from the change in valency and change in atomic

volume. The valence electrons from the foreign atom merge with the conduction electron number of the host with the result that the potential well at the substitution site has a different charge from that which exists at the host sites; in the mathematical treatment, the potential well has a different depth. The change in atomic volume causes the spatial dimensions of the impurity potential well to differ from that of the host.

When foreign atoms are randomly substituted into the host lattice and the crystal structure of the host is preserved, then provided that the foreign atoms do not interact with each other, the electrical resistivity increases in proportion to the number of foreign atoms added. Such a situation is realised in practice in dilute alloys where the alloy addition is typically less than 5%. Moreover, with such dilute alloys, the foreign atoms vibrate as though they were host atoms and consequently the additional contribution to the resistivity is temperature independent. This was first recognised experimentally in the 1860s by Matthiessen and Vogt and a simple rule, known as Matthiessen's rule, which applies to many dilute alloys, can be stated:

$$\rho_a(T) = \rho_p(T) + \rho(c) \tag{1.5}$$

where $\rho_a(T)$ and $\rho_p(T)$ are the temperature variations of the resistivities of the dilute alloy and the host and $\rho(c)$ is the concentration dependent resistivity of the foreign atoms, which is almost linear in concentration. There are deviations from this rule even for very dilute alloys, but with the exception of transition metal alloys involving the magnetic metals, the deviations are very small and for practical purposes can often be regarded as negligible.

1.6.2   Concentrated alloys

When the number of substitutional foreign atoms becomes large, for example when their concentration is greater than 5%, the assumption that they do not interact with each other is no longer valid and Matthiessen's rule breaks down. The distinction between host and foreign atom becomes obscure (with a 50 atomic percent binary alloy there is no distinction) and thus the $\rho_p(T)$ term of (1.4) loses its original significance. That is not to say the resistivity is temperature independent but rather the temperature dependence is not necessarily that of the major constituent of a concentrated alloy. As the concentration of foreign atoms increases, then so does $\rho(c)$ of (1.4) although it is no longer linear with concentration, and the result is that the contribution from the foreign atoms dominates.

To complicate matters further, according to the equilibrium phase diagram the alloy may exist as a single or multiphase, ordered or disordered solid solution depending on concentration and temperature. The data is presented in this handbook in terms of resistivity against temperature. Whilst this is the preferred means of presentation, it is sometimes easier to discuss the resistivity at a given temperature as a function of concentration.

The simplest situation in concentrated alloys is that of a binary system which exhibits complete solid solubility series at a given temperature. For such a disordered alloy, Nordheim [11] showed that the resistivity was of the form $\rho \propto c(l - c)$, which

can be written more generally as $\rho = A + c(1 - Bc)$, where A and B are constants which depend on the alloy series and c is the concentration of one of the components of the alloy. The Nordheim rule specifically relates to the impurity resistivity of concentrated alloys. With such alloys, impurity resistivity normally dominates and the rule can be applied to the total resistivity, especially for room temperature and below.

The above account relates to substitutional impurities which are randomly distributed in the host lattice. There are some alloy systems where for certain compositions the impurity atoms are located at distinct lattice positions, creating a long-range 'ordered' state with a degree of periodicity which is absent in the random state. At these compositions, where such a 'superlattice' exists, the resistivity of the ordered state is somewhat less than that of the random state. Generally, the random state is preferred at high temperatures and the long-range ordered state only occurs below a critical temperature. Thus, care should be exercised when using Nordheim's rule to estimate the resistivity of an alloy.

Phase-equilibrium diagrams of alloy systems indicate that the crystal structure of the alloy often changes with temperature. As mentioned above, these allotropes have different electronic structures which give rise to differences in the electrical resistivity, and this is manifest as a discontinuity in the resistivity/temperature plot, the discontinuity occurring at the boundary of the phase field. In a particular phase field, Nordheim's rule can in principle be applied, but the constants A and B will differ from phase to phase.

Alloy systems do not necessarily exist in a single phase. Indeed the mechanical properties of many engineering alloys depend on the coexistence of two or more phases. Each phase has its own characteristic resistivity which may exhibit a different temperature variation. For the binary two-phase systems, the resistivity may be regarded as lying between two limits corresponding to the two phases being elongated and aligned parallel to the current flux and where the two phases are platelets perpendicular to the current flow. If the volume fractions of the phases are known together with the characteristic resistivities of the individual single-phase alloys which bound the two phase fields, then the limits can be evaluated by regarding them as parallel and series networks. There is no general rule which governs whether the series or parallel configuration will exhibit the greater resistivity and in any case it is highly unlikely that these two somewhat idealised situations will be encountered in practice; likewise, there is no general rule to indicate whether or not the resistivity of the two-phase alloy will be greater or less than that of one of the individual bounding single-phase alloys; however, it might be anticipated that the resistivity would be less than that of the single-phase disordered alloy of the same composition and this is often observed.

In alloy systems where magnetic transformations occur, the change in long-range order is reflected in the resistivity and is often manifest as a change in slope of the resistivity/temperature curve at the critical or transition temperature. In general, the magnitude of the effect of long-range order on the resistivity is difficult to estimate. Ferromagnetic alloys usually contain one of the ferromagnetic pure metals whilst anti-ferromagnetic long-range ordering can be found in many of the alloy systems involving transition and rare-earth metals.

1.7   Semiconductors

As mentioned above, the band theory of solids provides a framework for classifying solids into metals, semiconductors and insulators, the last of which are not relevant to this handbook. In metals, there are continuous energy states above the Fermi energy due either to the bands not being completely filled or to the bands overlapping in energy, whereas in semiconductors there exists an energy gap, E_g, between the valence and conduction bands with the Fermi energy lying in the gap. In the pure elemental semiconductors such as germanium and silicon, electrons must be thermally excited into the conduction band (and as a result an equal number of holes created in the valence band) for these materials to behave as intrinsic conductors. At temperatures of around room temperature and below, the thermal energy, $k_B T$ (<0.03 eV), is small compared with E_g (≈ 0.7 eV for germanium, ≈ 1.1 eV for silicon), and as the number of carriers varies according to $\exp(-E_g/2k_B T)$, these materials are poor conductors; at absolute zero no thermal excitation can occur and they behave as insulators. Increasing the temperature causes the number of carriers to increase exponentially and hence the resistivity to fall. Small amounts of impurities can give rise to donor and acceptor levels within the energy gap which are very close, in energy terms, to the conduction band and valence band, respectively; the energy separation, E_i, may be comparable to the room temperature thermal energy ($k_B T = 0.026$ eV). As the number of carriers now varies as $\exp(-E_i/2k_B T)$, the result is that many more electrons are excited from the donor level into the conduction band (or correspondingly many more holes created in the valence band) at lower temperatures, leading to *n*-type (electron) and *p*-type (hole) conductivity. This conductivity, which is proportional to the concentration of impurities, can be several orders of magnitude larger than the intrinsic conductivity. On the other hand, the addition of some impurities to an already impure semiconductor can reduce the total number of carriers via compensation. Thus, the influence of impurities on the resistivity is in marked contrast to the case of metals. Because impurity concentration is usually very low and these materials are normally used in single crystal form where the defect concentration is low, phonon scattering is dominant, but the variation of resistivity with temperature is most strongly influenced by the variation in the number of carriers. For these reasons only the high temperature resistivity of the elemental semiconductors is given in the handbook.

1.8   Summary

To summarise these fundamental concepts, the resistivity of the pure metals is well understood. Reliable experimental data exists over a wide range of temperature and this in general conforms to theoretical expectations. For dilute alloys (less than 5 atomic percent), provided the increase in residual resistivity per atomic percentage impurity addition is known, the resistivity can be estimated with reasonable confidence from Matthiessen's rule. This rule holds remarkably well for many alloy systems although there are exceptions, notably when the host metal is one of the ferromagnets.

In concentrated alloys the situation is much more complicated. While Nordheim's rule can be used to obtain a fair estimate of the resistivity of some concentrated binary alloys, it has limited applicability. This is due to the many factors which influence the resistivity; these include atomic and magnetic long-range order, changes in crystal structure (or phase) as the alloy composition and temperature vary and coexistence of two or more phases. All these factors together make it almost impossible to make even a fair estimate of the resistivity of a given alloy, let alone its temperature dependence. If the resistivity of an alloy of near composition and similar heat treatment is known, then by using the principles outlined above, a reasonable estimate of the resistivity of the alloy in question may be obtained.

The purpose of this handbook is to provide a comprehensive compilation of experimental data in graphical form of resistivity versus temperature which we hope will be of assistance in this respect. Failing this, one must resort to the experimental determination of the resistivity; chapter 2 deals with some of the experimental methods of measuring resistivity.

1.9 Abbreviations

The graphical data presented in this book is based on either single crystals, bulk characteristics or alloy format. Some materials incorporate unusual resistivity characteristics when pretreated and these have been annotated with the abbreviations listed below.

AP	As prepared
MSG	Monoclinic space group
n/a	Data not available
OA	Oxygen annealed
OSG	Orthoclinic space group
Q	Quench temperature, K
δ	Thermal correction factor

Chapter 2
Measurement techniques

T. Farrell

2.1   Introduction

There are many techniques available for the determination of electrical resistivity. The simplest and most widely used is the so-called four probe method in which the resistance of a portion of the sample is measured when a direct current passes through the sample. This technique involves two current contacts and two voltage contacts attached to the sample. The four probe technique is applicable to the vast majority of metals and alloys and a variation of the method, the Van der Pauw technique, is widely used for the determination of the resistivity of semiconductor wafers. The technique is applicable over a wide range of temperature. However, difficulties may be experienced with contacts if, for example, the material is brittle or chemically reactive (as it may be in the molten state). For such materials, methods which do not rely on making physical contact to the sample are preferable; the most widely used non-contacting techniques are those based on eddy currents induced in the sample when it is placed in a magnetic field which varies with time. In the following paragraphs, the four probe technique and some of the eddy current techniques are briefly described.

The theoretical background to the four probe and eddy current methods can be demonstrated by the application of two of Maxwell's equations:

$$\operatorname{curl} \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} = -\mu \mu_0 \frac{\partial \boldsymbol{H}}{\partial t} \tag{2.1}$$

$$\operatorname{curl} \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t} = \frac{\boldsymbol{E}}{\rho} + \varepsilon \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} \tag{2.2}$$

In these equations, $\boldsymbol{E}$ is the electric field, $\boldsymbol{D}$ is the electric displacement, $\boldsymbol{H}$ is the magnetic field, $\boldsymbol{B}$ is the magnetic induction, ε_0 and μ_0 are the permittivity and permeability of free space, ε and μ are the relative permittivity and permeability of the sample and $\boldsymbol{J}$ is the current in unit cross-sectional area of the sample of resistivity ρ.

For a conducting sample, the displacement current $\partial \boldsymbol{D}/\partial t$ is negligible in comparison with $\boldsymbol{J}$ and thus (2.2) becomes

$$\operatorname{curl} \boldsymbol{H} = \boldsymbol{J} = \frac{\boldsymbol{E}}{\rho} \tag{2.2a}$$

Equation 2.2*a* is the basis for the four probe method. The expression $\boldsymbol{J} = \boldsymbol{E}/\rho$ is simply a statement of Ohm's law. Thus, writing $\boldsymbol{J} = I/A_S$ where I is the current in the sample of uniform cross-section A_S and V the voltage measured by two impedance probes separated by a distance L, the resistance R is

$$R = \rho \frac{L}{A_S} \qquad (2.3)$$

If the sample is cylindrical of radius a, the resistance is

$$R = \left(\frac{\rho}{a^2}\right) \frac{L}{\pi} \qquad (2.3a)$$

The basis for the eddy current methods is seen by substituting (2.1) into (2.2*a*):

$$\text{curl curl } \boldsymbol{H} = \nabla^2 \boldsymbol{H} = \frac{1}{\rho} \text{curl } \boldsymbol{E} = -\frac{\mu\mu_0}{\rho} \frac{\partial H}{\partial t} \qquad (2.4)$$

For a sample having isotropic magnetic and electrical properties, which is true of most polycrystalline materials, and where the magnetic field is aligned along the principal sample dimension (for example, along the axis of a cylinder, say the z direction), the vector equation (2.4) becomes scalar, and since $B = \mu\mu_0 H$ and the magnetic flux, ϕ, in the sample is $\phi = A_S B$, we have

$$\frac{\partial \phi}{\partial t} = -\frac{\rho}{\mu\mu_0} \frac{\partial^2 \phi}{\partial z^2} \qquad (2.4a)$$

Equation (2.4*a*) is the standard diffusion equation where the flux diffusivity (which has the dimensions of (length)^2/time) is $\rho/\mu\mu_0$. It governs how the magnetic flux in the sample changes with a time-dependent magnetic field. Solutions to the diffusion equation for various geometrical arrangements and different boundary conditions (for example, the time dependence of the magnetic field) are given in standard texts [12]. By way of illustration, consider a cylindrical sample of radius a which experiences a uniform magnetic flux, ϕ_0, which is suddenly removed at time $t = 0$; the average flux at time t is given by

$$\phi = \frac{4\phi_0}{a^2} \sum_{n=1}^{\infty} \frac{1}{\beta_n^2} \exp\left(-\beta_n^2 \left(\frac{\rho}{\mu\mu_0 a^2}\right) t\right) \qquad (2.5)$$

where the coefficients β_v are the positive roots of $\boldsymbol{J}_0(\beta) = 0$, $\boldsymbol{J}_0$ being the zero-order Bessel function. Thus, by observing the time dependence of the flux decay, the resistivity can be deduced. Details of this method along with other diffusion eddy current based methods involving periodic magnetic fields are discussed below. It is seen that in both (2.3) and (2.5) a term involving ρ/a^2 appears. The same term appears in other eddy current methods, which being diffusion based must have a term involving (length)^2 – or cross-sectional area – and this is important when considering the accuracy of the determination of ρ.

2.2   Four probe methods

These methods rely on the measurement of the resistance of the portion of the sample between the two voltage probes. For (2.3) to be applicable, the cross-sectional area of the sample should be uniform and the voltage probes should be connected to the sample in such a way that the length, L, can be accurately determined.

The preferred method of measuring the resistance is to use a Wheatstone bridge, which compares the unknown resistance of the sample with that of three standard resistors, one of which is a variable standard. As the bridge is a null method, calibration of the detector is not necessary. The accuracy with which the null point can be determined depends not only on the sensitivity of the detector but also on the relative magnitudes of the resistances of the arms of the bridge. A good general rule for optimum bridge operation is that the resistances in the four arms should be of the same order. With a well-designed bridge and sensitive detector, the bridge sensitivity can be very high and errors in the determination of resistivity arising from the resistance measurement can be regarded as being negligible.

Alternatively, the sample resistance can be measured using a constant current and measuring the probe voltage difference using a potentiometer or digital voltmeter; the latter has the advantage that it can be calibrated to give a direct reading of the resistance. To avoid zero errors it is usual practice to incorporate current reversal and take the average value of the two readings. Zero errors can arise not only from an incorrectly adjusted voltmeter but also from thermoelectric effects if a temperature gradient exists along the sample and the voltage leads, usually copper, have a different thermoelectric power from that of the sample being measured.

The accuracy with which the resistivity is determined from the resistance measurements can be dominated by the errors involved in the measurements of the sample cross-section and the separation of the voltage probes. This depends on the magnitude of A_S and L, which in turn is influenced by the magnitude of the resistivity through the need to have an accurate measurement of the resistance. For a pure metal with a resistivity of 5×10^{-8} ohm m, through which a current of 1 A passes and where the voltage is determined to an accuracy of 10 nV, then for a resistance measurement to an accuracy of 0.01%, the voltage between the probes should be 100 µV, giving a resistance of 10^{-4} ohm. From (2.3), L/A_S should be 2×10^3/m and thus can be satisfied realistically with a cylindrical sample of diameter 8 mm and with $L = 100$ mm. The power dissipated in the sample is 0.1 mW and this will not cause any significant heating.

Thus, for the majority of metals and alloys, the resistivity at temperatures above room temperature, cylindrical samples measuring about 10 mm in diameter and with L of about 50 to 100 mm are ideal shapes. Clearly, if this demands too large a quantity of material, the sample dimensions should be scaled down accordingly, but this will have the effect of increasing the errors in the measurement of L and A_S. At lower temperatures, particularly with annealed pure metals, the resistivity can be as low as 2×10^{-11} ohm m and this usually requires the sample to be in the form of a thin wire.

The measurement of L usually presents no problems. If mechanical clamps embodying 'knife-edge' contacts are used as the voltage probes, then the separation of appropriate datum marks on the clamps can be determined to plus or minus 0.02 mm with a travelling microscope; thus, the error introduced in the measurement of L is less than 0.1%.

The determination of A_S is more demanding. First, A_S should be uniform, and this can be checked by measuring the sample diameter (for the cylindrical sample) at various positions along L. It is preferable to use a non-contacting method for this measurement (if a micrometer is used, the contact pressure can lead to an erroneously low value for the diameter). Optical projection techniques and photographic enlargements can be used to get an accuracy of better than 0.1% in A_S, provided, of course, the sample is prepared to this accuracy.

Thus, provided care is taken in the measurement of L and A_S, the resistivity can readily be determined with an absolute accuracy of around 0.1% at and above room temperature. At cryogenic temperatures, in particular at liquid helium temperatures and with pure metals, the error in the determination of the resistance is maintained at negligible proportions by employing voltage detection equipment which involves superconducting elements and has much higher sensitivity.

2.3   Temperature variation of resistivity

With the four probe technique, the temperature variation of the resistivity can be determined quite simply by thermally attaching the sample to a heat sink, the temperature of which is controlled. The sample temperature can be measured using a suitable thermocouple attached to one of the voltage probes and any temperature gradients can be measured using a differential thermocouple with its two junctions thermally anchored to the two voltage probes; in this way, the mean sample temperature can be determined. The design of the furnace is not considered here, but for high-temperature work, a vacuum furnace is usually used to reduce the thermal load and prevent oxidation.

To overcome problems with thermoelectrically generated voltages, the voltage leads should be continuous to the wall of the vacuum vessel; likewise, for accurate temperature measurements it is preferable to use continuous thermocouple leads.

When varying the temperature, the change in sample dimensions due to thermal expansion should be taken into account, especially since L and A_S are usually carefully determined at room temperature. To illustrate the magnitude of the error which may be introduced by the neglect of thermal expansion, consider a cylindrical sample to which (2.3a) applies. At any temperature T, the resistance is

$$R_T = \rho_T \frac{L_0}{\pi a_0^2} \frac{(1 + \alpha \Delta T)}{(1 + \alpha \Delta T)^2} = \rho_T = \frac{L_0}{\pi a_0^2} (1 + \alpha \Delta T)^{-1}$$

where a is the thermal expansion coefficient, R_T is the measured resistance and ρ_T is the resistivity. Thus, the percentage error introduced is $\alpha \Delta T \times 100$. Taking a representative value of $\alpha = 15 \times 10^{-6}$ for most metals and alloys, it is readily

appreciated that the error can be comparable to the accuracy in the determination of the resistivity for a ΔT of 100 K.

2.4   Eddy current methods

Several techniques which rely on induced eddy currents for the determination of resistivity have evolved, the simplest of which correspond to the situations where the applied magnetic field is periodic, for example varying sinusoidally with time, and where the field is a step function being suddenly switched from zero to a preset constant value or conversely switched from a steady value to zero. Whilst these elegant techniques overcome the need for electrical contact to the sample, they do have characteristic features which can give misleading results.

First, it is important to recognise that the eddy currents are not uniformly distributed throughout the sample when a periodic magnetic field is applied. They decay exponentially from the sample surface with a measure of the decay being the 'skin depth'. The skin depth, δ, is given by

$$\delta = \left(\frac{\pi f \mu \mu_0}{\rho} \right)^{-1/2}$$

and is the depth at which the eddy currents have fallen to $1/e$ of their surface value. If the whole of the sample is to be examined, then, in the case of the periodically varying magnetic field, the frequency, f, should be chosen so that δ is not significantly less than the sample dimension, which, in the case of a cylinder with the magnetic field parallel to the cylinder axis, is the cylinder radius. If δ is significantly less than the sample dimensions, then surface features such as roughness and contaminant films can affect the resistivity measurements. It must be emphasised that the only situation where uniform current density occurs is in the direct current measurements on uniform cross-section samples as discussed in the four probe method.

Second, the magnetic field can directly influence the motion of the electrons within the sample (in addition to 'indirect' influence via induction which gives rise to the eddy currents), leading to additional resistance over that caused by scattering. This 'magnetoresistance' is dependent on the magnitude of the applied magnetic field and its occurrence can be checked by varying the field strength.

These techniques are well suited to the determination of the resistivity of weakly magnetic materials where the relative permeability, μ, can safely be regarded as unity. However, some caution should be exercised when dealing with ferromagnetic and strongly paramagnetic materials or materials which exhibit magnetic transformations where μ is neither constant nor unity.

The most convenient means of applying a magnetic field is to place the conducting sample in a coil. With the step function methods, the resistivity is determined by observing the change of flux in the sample as a function of time after the field has suddenly been applied or removed; this is described for the case of field removal by (2.5). For periodically varying fields, the difference between the impedance of the loaded and empty coil is measured.

2.5   Step function methods

The basis of this method has already been mentioned. A convenient arrangement is to insert the sample into a coil, apply a direct current to the coil for sufficient time to ensure complete flux penetration into the sample and then de-energise the coil by opening a switch. A simple circuit is shown in Fig. 2.1. The flux decay is detected by a secondary coil wound over the central region of the energising coil. The time dependence of the average flux, ϕ, in a cylindrical sample after removing the magnetic field is given by (2.5). If there are N turns on the second coil then the voltage induced in that coil is

$$-N\frac{\partial\phi}{\partial t}$$

Using the relationship between ϕ and magnetic field H

$$\phi = \pi a^2 \mu\mu_0 H$$

and differentiating (2.5) with respect to time and multiplying by N, the secondary coil voltage is obtained:

$$V = 4\pi N\rho H_0 \sum_{n=1}^{\infty} \exp\left(-\beta_n^2\left(\frac{\rho}{\mu\mu_0 a^2}\right)t\right)$$

The voltage decays as a sum of exponential factors. The first three coefficients β_n^2 have the values 5.784, 30.470 and 74.892; thus, for longer times, the decay is a simple exponential governed by β_1^2. To illustrate this, consider the exponential term involving β_2 to contribute a maximum of 0.1% of the contribution from β_1. For this condition to apply:

$$\exp\left(-\left(24\cdot676\left(\frac{\rho}{\mu\mu_0 a^2}\right)t\right)\right) \le 10^{-3}$$

Thus, for a material with $\rho = 5 \times 10^{-8}$ ohm m, $a = 5 \times 10^{-3}$ m and $\mu = l$, the time should be greater than 1.75×10^{-4} s in which case the sum of the exponential
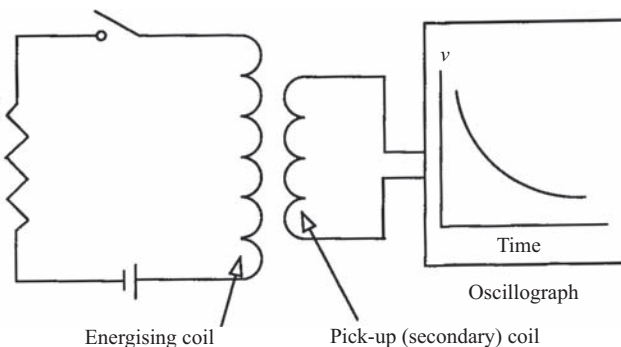
Figure 2.1   Simple circuit for the step function method

factors is approximately 0.2. The measured voltage at this time is $1.25 \times 10^{-5} H_0$ V and after $t = 5 \times 10^{-4}$ s the voltage has decayed to $6.25 \times 10^{-7} H_0$ V. The voltage/time variation can be measured and stored using a suitable oscilloscope.

2.6 Periodically varying fields

The impedance, Z_L, of a magnetic field coil into which a conducting sample is placed (a loaded coil) comprises resistive and reactive components:

$$Z_L = R_L + iX_L$$

The resistance R_L and reactance X_L of the loaded coil are given by

$$R_L = R_0 + R_1$$
$$X_L = X_0 + X_1$$

where R_0 and X_0 refer to the empty solenoid and R_1 and X_1 are the resistive and reactive contributions from the eddy currents induced in the sample. In fact, R_1 and X_1 measure the out-of-phase and in-phase flux in the sample.

In general

$$R_1 = A'X_0 F_R(y)$$
$$X_1 = A'X_0 F_X(y)$$
$$\text{or}\quad \frac{X_1}{R_1} = \frac{F_X(y)}{F_R(y)} = F_{XR}(y)$$

where the constant A' is a measure of the ratio of the cross-sectional area of the sample to that of the coil and y is a parameter involving the skin depth and the dimension of the sample. Analytical expressions of the coil functions $F_X(y)$, $F_R(y)$ and hence $F_{XR}(y)$ can be derived for the simpler geometrical shapes such as 'infinite' cylinders, in which case y is given by

$$y = \frac{\sqrt{2}a}{\delta} = (2\pi\mu\mu_0)^{1/2} \left(\frac{fa^2}{\rho}\right)^{1/2}$$

where a is the radius, as before, and the coil 'filling factor', A', is simply A_S/A_C, where A_C is the cross-sectional area of the coil. The coil functions for cylindrical geometry are shown in Figs. 2.2 and 2.3 and for such a geometry these figures can be used directly to obtain ρ once X_0, X_1 and R_1 have been measured.

Samples of irregular geometry, for which analytic expressions cannot be derived, can be used but the coil/sample system should be calibrated over a range of frequencies using a 'standard' specimen of known resistivity, ρ_S, having identical shape to that to be determined. The experimentally determined R_S/X_0, X_S/X_0 and X_S/R_S give $A'F_R(y)$, $A'F_X(y)$ and $F_{XR}(y)$, respectively (X_S and R_S refer to the calibration with the standard resistivity specimen). There are advantages in using $F_{XR}(y)$ as this eliminates the need to know the coil filling factor which, for non-simple geometries, is difficult to calculate.
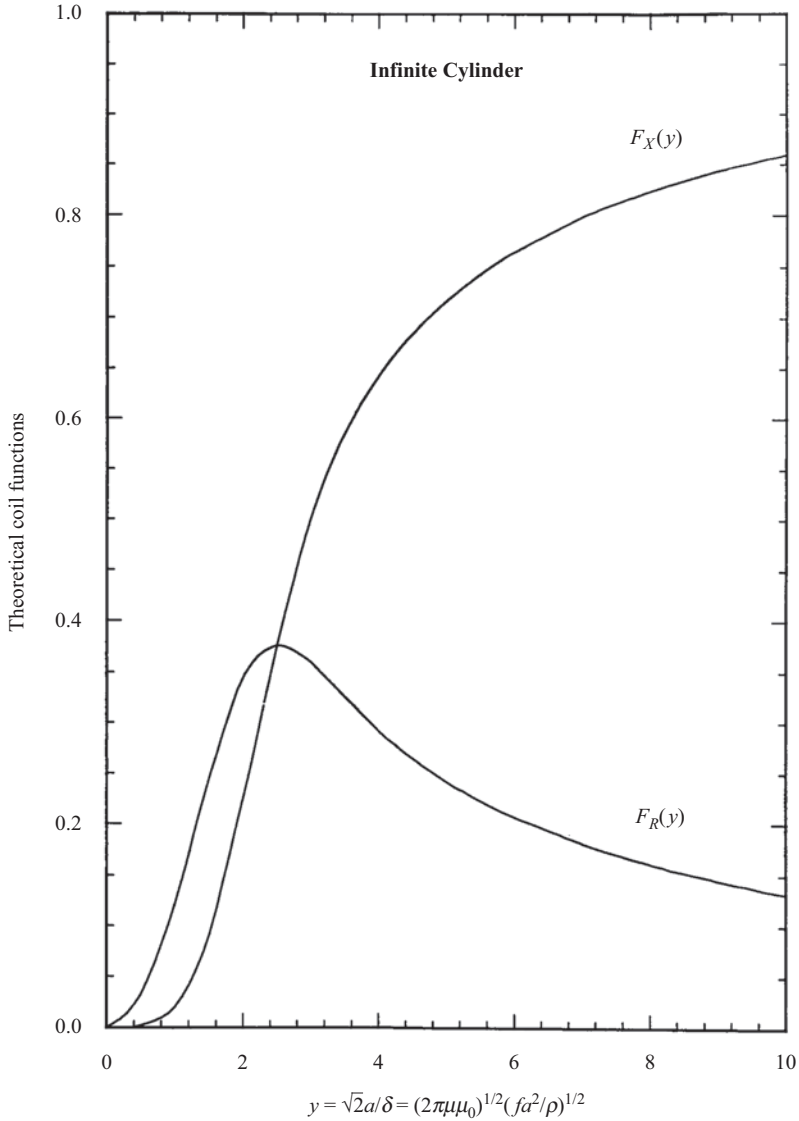
Figure 2.2   Coil functions $F_R(y)$ and $F_X(y)$ for an infinite cylinder

Having determined the empty coil parameter and obtained the coil functions, a single frequency measurement is sufficient to determine the resistivity of the unknown sample. The choice of frequency is important for two reasons. First, as mentioned beforehand, it is desirable that $\delta > a$, and second, since the resistivity determination involves the subtraction of the unloaded coil measurements from the
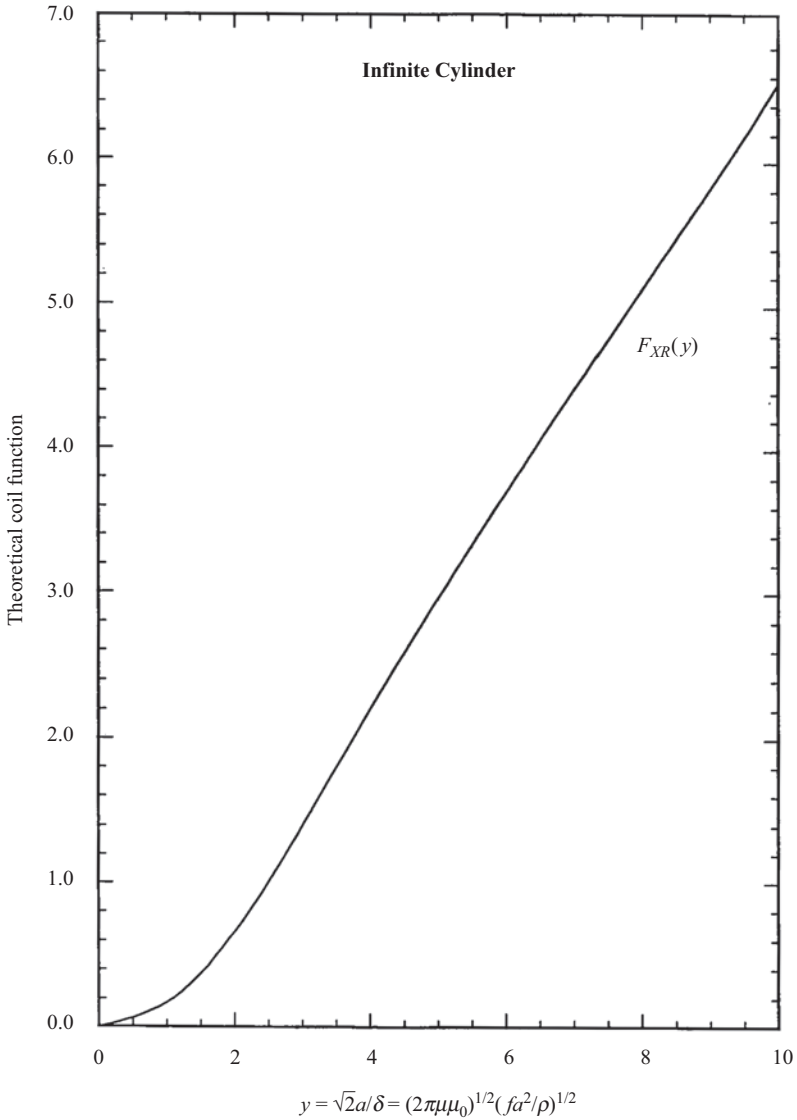
Figure 2.3   Coil function $F_{XR}(y)$ for an infinite cylinder

loaded coil measurements, it is desirable to have a large difference between the two sets of measurements. This can be illustrated by reference to Fig. 2.2 and again taking a cylindrical sample of radius 5 mm and resistivity of 5×10^{-8} ohm m. $F_X(y)$ and $F_R(y)$ are both greater than 0.2 in the range from $y = 2$ to 5.5 and this corresponds to $f = 1$ to 7.5 kHz. At $f = 1.0$ kHz, the skin depth in the above material

is 3.6 mm, whilst at $f = 7.5$ kHz, the skin depth is 1.3 mm. If the criterion of $\delta = a = 5$ mm is used, the frequency is 500 Hz giving $y = 1.4$; $F_X(y)$ and $F_R(y)$ are reduced to 0.07 and 0.22, respectively. This implies that the maximum value of X_L/X_0 is 1.07 (taking $A' = 1$), which imposes a more stringent demand on the experimental determination of X_L and X_0. At higher frequencies (7.5 kHz), the experimental demands are relaxed but skin depth considerations may affect the result.

2.7   Inductive techniques

2.7.1   Self-inductance

The coil should be longer than the sample to avoid end effects, thus ensuring uniformity of the magnetic flux in the sample. Coil design details are beyond the scope of this account, but taking into consideration such factors as low thermal dissipation, maximum coil filling factor, small magnetic fields, etc., then for a cylindrical sample of diameter about 10 mm, R_0 and $2\pi f X_0$ ($f = 10^3$ Hz) can each be a few ohms, giving a coil impedance of around 10 ohms.

The loaded and unloaded coil impedances are measured using an appropriate variable frequency bridge. Two self-inductance bridge networks are shown in Fig. 2.4. The Anderson bridge, Fig. 2.4*b*, has the advantage that it avoids the use of variable standard inductors or capacitors. Taking the coil current to be in the milliampere range (for low thermal dissipation and low magnetic fields) and following the general rule for optimum bridge operation, the driving voltage of the audio-frequency oscillator is in the 0.1 to 1.0 V range. Using a tuned detector, the sensitivity of the bridge can be higher than 0.005%, and with an appropriately chosen frequency and good coil filling factor, R_1 and $2\pi f X_1$, can be around $0.15 \times 2\pi f X_0$ implying that R_1 and X_1 can be measured to an accuracy of 0.05%. The error in y is that associated with the accuracy to which a can be measured and this has been discussed in connection with the four probe method.

The uncertainty in ρ arises from the uncertainties in y^2 (and hence a^2) and if $F_X(y)$ and $F_R(y)$ are used the uncertainties in A', which involve both a^2 and d^2 (d is the coil diameter); if $F_{XR}(y)$ is used the uncertainties are reduced as A' is not required. If a non-simple shape is used which necessitates experimental determination of $F_X(y)$ and $F_R(y)$, the errors are compounded by the dimensions of both the standard and unknown samples. Taking all these factors into consideration the accuracy in ρ when determined using the self-inductance technique is likely to be in the region of 0.1% with the lowest uncertainties being achieved with a uniform cross-section cylindrical sample.

2.7.2   Mutual inductance

The use of a secondary coil wound over the central region of the primary coil has the advantage of eliminating end effects and offers the prospect of examining regions of the sample along its length. The analysis of the coils for mutual inductance is quite complex. As an approximation, the reactance and resistance of a suitable unloaded
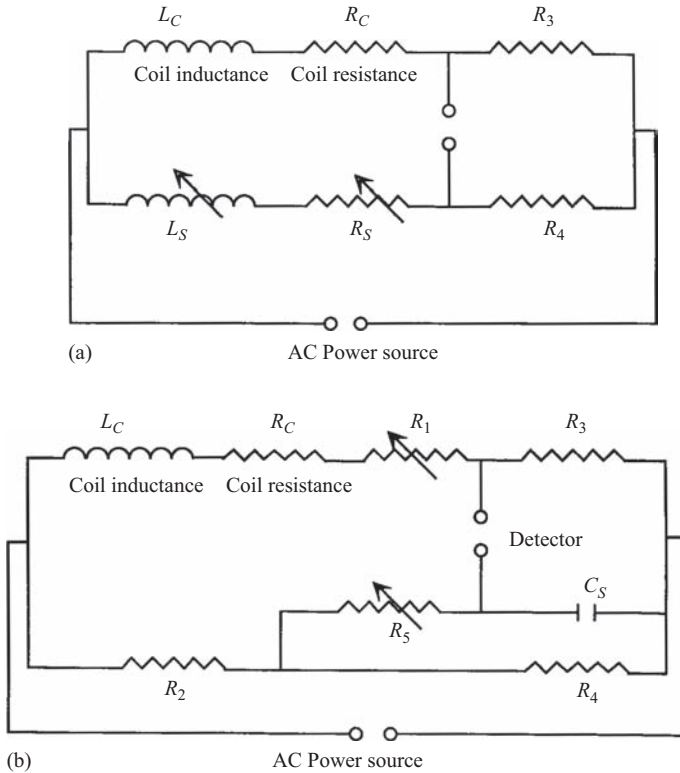
Figure 2.4 Typical bridges for the determination of self-inductance. (a) Typical bridge using standard inductors; (b) Anderson bridge

coil system is scaled down from the self-inductance and resistance of the primary coil by the turns ratio. Thus, a typical system will have a mutual inductance in the region of 100 μH (as opposed to a few millihenries for the single-coil self-inductance).

The determination of mutual inductance is most readily achieved by making a direct comparison with a variable standard mutual inductance, connecting the primary windings of both standard and unknown in series to an audio-frequency oscillator and connecting the secondary windings in series opposition so that the induced voltages oppose each other. In principle, the detector which is in series with the secondaries shows a null reading when the mutual inductances and unknown inductors are equal. In practice, because a resistance element exists, it is almost impossible to obtain a balance. The so-called Hartshorn bridge, shown in Fig. 2.5, overcomes this difficulty. The technique requires a balance to be obtained in the unloaded system by adjusting M_S and R. The sample is then inserted and the balance is restored by varying M_S and R by ΔM_S and ΔR from the unloaded condition. Recognising that R_1^+ and X_1^+ are measures of the out-of-phase and in-phase flux associated with the eddy currents, R_1^+ is given by ΔM_S and X_1^+ by $\Delta R/2\pi f$. As with the self-inductance technique,
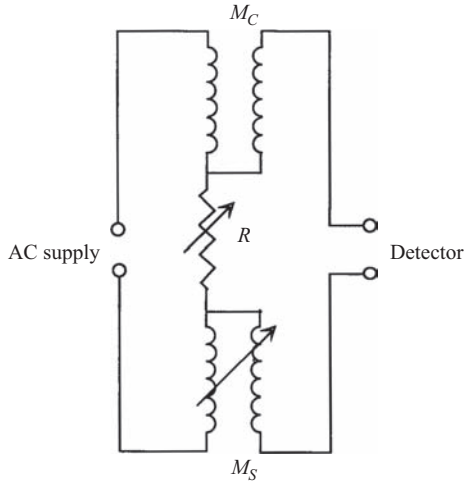
Figure 2.5 The Hartshorn mutual inductance bridge. M_C = mutual inductance of the coil, M_S = variable standard mutual inductance

the value of y is then obtained from the calibrated coil function or, if cylindrical samples are used, from the theoretical coil functions shown in Figs. 2.2 and 2.3.

The mutual inductance technique relies on exactly the same parameters as the self-inductance method; the uncertainties involved are again those associated with the measurement of sample and coil dimensions and hence the achievable accuracy in the determination of the resistivity is similar.

2.7.3   Inductive techniques and temperature variations

The primary purpose of using eddy current techniques is to avoid physical contact with the sample. When determining the resistivity as a function of temperature, the sample should be in an isothermal enclosure with the temperature of the enclosure monitored with an appropriate thermometric device such as a thermocouple, resistance thermometer or pyrometer. The use of an isothermal enclosure virtually eliminates thermoelectrically generated voltages.

When the highest accuracy is sought, the effects of thermal expansion must be taken into account and these effects enter through expansion of the sample and the coils (in the four probe method only the expansion of the sample needs to be considered).

The reactance of the unloaded coil is related to its dimension via $X_0 = $ constant $\times$ d_c^2/l_c, where d_c and l_c are the coil diameter and length, respectively. The effect of an increase in temperature, ΔT, is to increase X_0 by $\alpha \Delta T \times 100\%$ where α may be taken to be the coefficient of expansion of the coil windings. The magnitude of the change is similar to that discussed in connection with the variation of resistance with temperature in the four probe method.

Neglecting the lead resistances, R_0 is proportional to l_w/d_w^2, where l_w and d_w are the wire length and diameter. Assuming the coil is tightly wound then $d_w \approx B_c l_c$. and $l_c \approx C_c l_c$ where B_c and C_c are constants involving the number of turns on the coil and the number of layers of windings. R_0 is therefore proportional to d_c/l_c^2 and the effect of a temperature increase of ΔT is to decrease R_0 by $\alpha \Delta T \times 100\%$. Again, the magnitude of the effect can easily exceed the accuracy with which the resistivity can be determined and corrections for thermal expansion should be made.

The sample dimensions enter through the parameter y which is proportional to $(r/a^2)^{1/2}$; thus, if the thermal expansion behaviour of the sample is known, a simple correction can be applied for y.

However, it is not just a simple matter of correcting the impedance measurements for thermal expansion as is the case with the resistance measurements in the four probe method. Since R_0 and L_0 change with temperature, the bridge balance conditions also change. Thus, for the most reliable results, the implication is that the equipment should have provision for withdrawing the sample from the coil to enable R_0 and L_0 as well as R_L and X_L to be measured at each temperature.

The coil filling factor is also affected by thermal expansion. If F_X, F_R are used to determine the resistivity, then a simple correction for thermal expansion (sample/coil) can be applied; this is not necessary if F_{XR} is used.

This account of experimental techniques concludes with a few remarks about an interesting method of resistivity measurement which involves induced eddy currents and as such avoids the use of electrical contact. Unlike the eddy current techniques discussed above, it does not rely on electrical measurements. The technique involves a rotating uniform magnetic field such as that produced by the stators of a polyphase induction motor. When a cylindrical sample is placed in the field, the induced eddy currents interact with the flux causing the sample to experience a torque, Γ, given by

$$\Gamma = \frac{\pi \omega_r \mu^2 \mu_0^2 l a^4 H^2}{4\rho}$$

where ω_r is the relative angular velocity of H and the sample. If the sample's motion is restrained by a torsion wire, it will rotate to a fixed position where Γ is balanced by the reaction in the torsion wire, enabling the above expression to be used with ω_f, the angular velocity of the field, replacing ω_r. Measurement of the deflection by the incorporation of a mirror into the torsion wire suspension and the use of optical levers gives an accurate measurement of Γ. The resistivity, ρ, is then determined using the above expression. This technique is more sensitive to the sample dimensions than the electrical techniques and is thus inherently less accurate. Furthermore, when using this method to determine the temperature variation of the resistivity, it is important that corrections for thermal expansion be applied.

Chapter 3
Explanation of graphs
G. Dyos

3.1 Data analysis

The majority of the data presented in this handbook has been gleaned from material published over the last two decades. The data has been extracted from the original published paper or book. The interpretation of the data is that of the original author except where an obvious error has occurred in the publishing of tabular material. Otherwise, every effort has been made to ensure the accuracy of the transcripted original data.

3.2 Catalogue system for materials

The catalogue system used in this book is based on two levels. First, the materials are listed in alphabetical order; where a material has several elements, they are listed in order of decreasing atomic percentage. Should a material have elements all having equal atomic percentage then they are listed in alphabetical order.

Data which has been presented in the original paper in graphical form and extracted is indicated by an asterisk (*) against the reference number in question. Data presented, in the original form, in tabular format is indicated by the absence of an asterisk against the reference number. Data from various sources which has been surveyed by an author to determine a best fit of that data is indicated by an 'R' after the reference. Data included in that survey is not represented in this handbook.

If the material is a disordered crystalline compound, the letter 'D' is placed after the reference number and similarly the letter 'A' is used if the material is amorphous. It should be noted that the vast majority of authors do not indicate whether an allowance for thermal expansion has been applied to the resistivity of the material. Where the purity of an element has not been stated in the original paper, but the information greatly extends the range of resistivity, this has been denoted by '%na'.

3.3 Material composition

The purity of the elements in this book is expressed in terms of the weight percentage of the elements present.

All the compounds listed in this handbook are expressed in terms of atomic percentages, that is, the number of atoms of an element expressed as a percentage of the total number of atoms present in one molecule of the material.

Where compounds have been listed in the original reference as weight percentages, these have been converted into atomic percentages.

Chapter 4
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Chapter 5

Index of materials

Resistivity – pressure effects

Normalised resistance, pressure and resistance effects

Chapter 6
Material resistivity graphs

6.1 Electrical resistivity as a function of temperature

Aluminium Ytterbium

Ytterbium (at %)

33.33 Ref 10*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Antimony Cobalt Titanium - 2

Cobalt, Titanium (at %)

33.22, 33.22 Ref 119*
33.44, 33.11 Ref 119*
33.50, 32.99 Ref 119*

Resistivity, ohm m × 10^{-8}

Temperature, K

Antimony Cobalt Titanium Indium

Cobalt, Titanium, Indium (at %)

33.11, 33.11, 0.66 Ref 119*

Antimony Cobalt Titanium Iron

Cobalt, Titanium, Iron (at %)

33.11, 33.11, 0.66 Ref 119*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Antimony(1+δ) Cobalt Titanium Manganese

($\delta = 0.05$)

($\delta = 0$)

($\delta = 0.05$)

($\delta = 0$)

Cobalt, Titanium, Manganese (at %)

32.73, 32.73, 0.164 Ref 119*
33.28, 33.28, 0.166 Ref 119*
32.68, 32.68, 0.327 Ref 119*
33.22, 33.22, 0.332 Ref 119*

Resistivity, ohm m × 10^{-8}

Temperature, K

Antimony Cobalt Titanium Nickel

Cobalt, Titanium, Nickel (at %)

33.00, 33.00, 0.99 Ref 119*

Resistivity, ohm m × 10^{-8}

Temperature, K

Antimony Cobalt Titanium Niobium

Cobalt, Titanium, Niobium (at %)
33.22, 33.22, 0.33 Ref 119*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Antimony Cobalt Titanium Tellurium

Cobalt, Titanium, Tellurium (at %)

33.00, 33.00, 0.99 Ref 119*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Antimony Cobalt Titanium Tin

Cobalt, Titanium, Tin (at %)

33.00, 33.00, 0.99 Ref 119*

Antimony Cobalt Titanium Vanadium

Cobalt, Titanium, Vanadium (at %)

- 33.33, 31.67, 1.67 Ref 119*
- 33.33, 30.00, 3.33 Ref 119*
- 33.33, 28.33, 5.00 Ref 119*
- 33.33, 26.67, 6.67 Ref 119*
- 33.33, 20.00, 13.33 Ref 119*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Arsenic Calcium Fluorine Iron - 1

Calcium, Fluorine, Iron (at %)

25.00, 25.00, 25.00 Ref 208*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Arsenic Calcium Fluorine Iron - 2

Calcium, Fluorine, Iron (at %)

25.00, 25.00, 25.00, Ref 184*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Arsenic Calcium Fluorine Iron Chromium

Calcium, Fluorine, Iron, Chromium (at %)
25.00, 25.00, 23.75, 1.25 Ref 208*
25.00, 25.00, 22.50, 2.50 Ref 208*
25.00, 25.00, 21.50, 3.50 Ref 208*
25.00, 25.00, 20.00, 5.00 Ref 208*

Arsenic Calcium Fluorine Iron Cobalt - 1

Calcium, Fluorine, Iron, Cobalt (at %)

25.00, 25.00, 23.75, 1.25 Ref 208*
25.00, 25.00, 23.25, 1.75 Ref 208*
25.00, 25.00, 22.50, 2.50 Ref 208*
25.00, 25.00, 21.25, 3.75 Ref 208*
25.00, 25.00, 20.00, 5.00 Ref 208*
25.00, 25.00, 18.50, 6.50 Ref 208*

Arsenic Calcium Fluorine Iron Cobalt - 2

Calcium, Fluorine, Iron, Cobalt (at %)
— 25.00, 25.00, 22.50, 2.50 Ref 104*
— 25.00, 25.00, 21.25, 3.75 Ref 104*
— 25.00, 25.00, 20.00, 5.00 Ref 104*

Resistivity, ohm m × 10^{-8}

Temperature, K

Arsenic Calcium Fluorine Iron Copper

Calcium, Fluorine, Iron, Copper (at %)

25.00, 25.00, 23.75, 1.25 Ref 208*

Arsenic Calcium Fluorine Iron Nickel

Calcium, Fluorine, Iron, Nickel (at %)
- 25.00, 25.00, 23.75, 1.25 Ref 208*
- 25.00, 25.00, 22.50, 2.50 Ref 208*
- 25.00, 25.00, 21.25, 3.75 Ref 208*
- 25.00, 25.00, 20.00, 5.00 Ref 208*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Arsenic Cerium Iron Oxygen Fluorine

Cerium, Iron, Oxygen, Fluorine (at %)
25.00, 25.00, 21.00, 4.00 Ref 235*
25.00, 25.00, 24.00, 1.00 Ref 132*
25.00, 25.00, 23.00, 2.00 Ref 132*
25.00, 25.00, 22.00, 3.00 Ref 132*
25.00, 25.00, 21.00, 4.00 Ref 132*
25.00, 25.00, 20.00, 5.00 Ref 132*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Arsenic Cerium Nickel Oxygen

Cerium, Nickel, Oxygen (at %)
25.00, 25.00, 25.00 Ref 203*

Resistivity, ohm m $\times 10^{-8}$ (y-axis)

Temperature, K (x-axis)

Arsenic Cerium Nickel Oxygen Fluorine

Cerium, Nickel, Oxygen, Fluorine (at %)
25.00, 25.00, 22.50, 2.50 Ref 203*

Resistivity, ohm m × 10^{-8}

Temperature, K

Arsenic Dysprosium Iron Oxygen

Dysprosium, Iron, Oxygen ($\delta = 0$) (at %)

25.00, 25.00, 25.00 Ref 164*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Arsenic Europium Fluorine Iron

Resistivity, ohm m × 10^{-8}

Europium, Fluorine, Iron (at %)

25.00, 25.00, 25.00 Ref 184*

Temperature, K

Arsenic Fluorine Iron Neodymium Strontium

Fluorine, Iron, Neodymium, Strontium (at %)
○— 25.00, 25.00, 12.50, 12.50 Ref 229*
□— 25.00, 25.00, 13.50, 11.50 Ref 229*
◇— 25.00, 25.00, 16.00, 9.00 Ref 229*
×— 25.00, 25.00, 17.50, 7.50 Ref 229*
+— 25.00, 25.00, 19.75, 5.25 Ref 229*

Arsenic Fluorine Iron Strontium Neodymium

Fluorine, Iron, Strontium, Neodymium (at %)
25.00, 25.00, 23.50, 1.50 Ref 229*
25.00, 25.00, 19.25, 5.75 Ref 229*
25.00, 25.00, 16.00, 9.00 Ref 229*
25.00, 25.00, 14.25, 10.75 Ref 229*

Arsenic Fluorine Iron Strontium Samarium

Fluorine, Iron, Strontium, Samarium (at %)

25.00, 25.00, 20.00, 5.00 Ref 183*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Arsenic Gadolinium Iron Oxygen Fluorine

Gadolinium, Iron, Oxygen, Fluorine (at %)

25.00, 25.00, 21.00, 4.00 Ref 203*

Arsenic Iron Barium Potassium - 1

Iron, Barium, Potassium (at %)

- ⊙ 40.00, 15.40, 4.60 Ref 185*
- □ 40.00, 15.00, 5.00 Ref 185*
- ◇ 40.00, 14.40, 5.60 Ref 185*
- ✕ 40.00, 12.00, 8.00 Ref 185*
- + 40.00, 12.00, 8.00 Ref 213*

Arsenic Iron Barium Potassium - 2

Iron, Barium, Potassium (at %)

40.00, 18.00, 2.00 Ref 197*
40.00, 16.00, 4.00 Ref 197*
40.00, 14.00, 6.00 Ref 197*

Resistivity, ohm m × 10^{-8}

Temperature, K

Arsenic Iron Calcium

Iron, Calcium (at %)

40.00, 20.00 Ref 188*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Arsenic Iron Calcium Sodium

Iron, Calcium, Sodium (at %)

40.00, 10.00, 10.00 Ref 188*

Arsenic Iron Gadolinium Oxygen

Iron, Gadolinium, Oxygen (at %)
25.00, 25.00, 25.00 Ref 234*

Arsenic Iron Lanthanum Oxygen

Iron, Lanthanum, Oxygen (at %)
25.00, 25.00, 25.00 Ref 211*
25.00, 25.00, 25.00 Ref 101*
25.97, 25.97, 22.08 Ref 120*

Resistivity, ohm m × 10^{-8}

Temperature, K

Arsenic Iron Lanthanum Oxygen Fluorine Sodium

Iron, Lanthanum, Oxygen, Fluorine, Sodium (at %)
25.00, 22.00, 22.50, 2.50, 2.50 Ref 207*
25.00, 21.25, 21.25, 3.75, 3.75 Ref 207*
25.00, 20.00, 20.00, 5.00, 5.00 Ref 207*

**Arsenic Iron Lanthanum Oxygen
Fluorine Ytterbium**

Iron, Lanthanum, Oxygen, Fluorine, Ytterbium (at %)
—⊖— 25.00, 22.50, 20.00, 5.00, 2.50 Ref 169*
—⊟— 25.00, 20.00, 20.00, 5.00, 5.00 Ref 169*

Resistivity, ohm m × 10^{-8}

Temperature, K

Arsenic Iron Neodymium Oxygen

Iron, Neodymium, Oxygen
⊖ 25.00, 25.00, 25.00 Ref 203*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Arsenic Iron Neodymium Oxygen Fluorine

Iron, Neodymium, Oxygen, Fluorine (at %)
25.00, 25.00, 24.00, 1.00 Ref 203*
25.00, 25.00, 23.00, 2.00 Ref 203*
25.00, 25.00, 22.00, 3.00 Ref 203*
25.00, 25.00, 21.00, 4.00 Ref 203*

Resistivity, ohm m × 10^{-8}

Temperature, K

Arsenic Iron Oxygen Gadolinium Cerium Fluorine

Iron, Oxygen, Gadolinium, Cerium, Fluorine (at %)
25.00, 21.00, 17.50, 7.50, 4.00 Ref 235*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Arsenic Iron Oxygen Praseodymium

Iron, Oxygen, Praseodymium (at %)
25.00, 25.00, 25.00 Ref 210*

Arsenic Iron Oxygen Samarium

Resistivity, ohm m $\times$ 10^{-8}

Temperature, K

Iron, Oxygen, Samarium (at %)
25.00, 25.00, 25.00 Ref 168*
25.00, 25.00, 25.00 Ref 189*

Arsenic Iron Oxygen Yttrium

Iron, Oxygen, Yttrium (at %)
25.00, 25.00, 25.00 Ref 164*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Arsenic Iron Potassium

Iron, Potassium (at %)

⊖ 40.00, 20.00 Ref 99*

Temperature, K

Resistivity, ohm m $\times 10^{-8}$

Arsenic Iron Praseodymium Oxygen Fluorine

Iron, Praseodymium, Oxygen, Fluorine (at %)
25.00, 25.00, 22.25, 2.75 Ref 194*

Resistivity, ohm m × 10⁻⁸ *(y-axis)*

Temperature, K *(x-axis)*

Arsenic Iron Samarium Oxygen

Iron, Samarium, Oxygen (at %)
25.97, 25.97, 22.08 Ref 120*

Resistivity, ohm m × 10^{-8}

Temperature, K

Arsenic Iron Samarium Oxygen Fluorine - 1

Iron, Samarium, Oxygen, Fluorine (at %)

—⊖— 25.00, 25.00, 21.25, 3.75, Ref 220*
—☐— 25.00, 25.00, 20.00, 5.00, Ref 220*
—◇— 25.00, 25.00, 17.50, 7.50, Ref 220*
—✕— 25.00, 25.00, 15.00, 10.00, Ref 220*

Resistivity, ohm m $\times$ 10^{-8}

Temperature, K

Arsenic Iron Samarium Oxygen Fluorine - 2

Iron, Samarium, Oxygen, Fluorine (at %)
⊖ 25.00, 25.00, 23.25, 1.75 Ref 189*
⊡ 25.00, 25.00, 22.50, 2.50 Ref 168*

Arsenic Iron Strontium

Iron, Strontium (at %)
40.00, 20.00 Ref 185*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Arsenic Iron Thulium Oxygen Fluorine

Iron, Thulium, Oxygen, Fluorine (at %)
25.00, 25.00, 21.00, 4.00 Ref 203*

Arsenic Lanthanum Oxygen Iron Nickel

Lanthanum, Oxygen, Iron, Nickel (at %)
25.00, 25.00, 24.00, 1.00 Ref 206*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Arsenic Oxygen Praseodymium Iron Cobalt

Oxygen, Praseodymium, Iron, Cobalt (at %)
25.00, 25.00, 23.75, 1.25 Ref 210*
25.00, 25.00, 22.50, 2.50 Ref 210*
25.00, 25.00, 21.25, 3.75 Ref 210*
25.00, 25.00, 20.00, 5.00 Ref 210*
25.00, 25.00, 17.50, 7.50 Ref 210*

Resistivity, ohm m × 10^{-8}

Temperature, K

Barium Cobalt Germanium

Cobalt, Germanium (at %)

31.97, 6.80 Ref 165*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Bismuth Antimony

Antimony (at %)

12.00 Ref 205*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Bismuth Antimony Nickel

Antimony, Nickel (at %)

⊖ 11.88, 0.99 Ref 205*
⊟ 11.65, 2.91 Ref 205*
◇ 11.42, 4.76 Ref 205*
✕ 10.91, 9.09 Ref 205*

Resistivity, ohm m $\times$ 10^{-8}

Temperature, K

Bismuth Cerium Platinum

Cerium, Platinum (at %)

30.00, 30.00 Ref 39*

Resistivity, ohm m × 10^{-8}

Temperature, K

Boron Aluminium

Aluminium (at %)

33.33 Ref 232*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Boron Aluminium Magnesium

Aluminium, Magnesium (at %)
- ⊖ 20.00, 13.33 Ref 232*
- ⊟ 26.66, 6.67 Ref 232*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Boron Cadmium Magnesium

Cadmium, Magnesium (at %)

16.67, 16.67 Ref 105*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Boron Magnesium

Magnesium (at %)
— ◯ — 33.33 Ref 232*
— ☐ — 33.33 Ref 62*
— ◇ — 33.33 Ref 111*

Boron Magnesium Aluminium - 1

Resistivity, ohm m × 10⁻⁸

Temperature, K

Magnesium, Aluminium (at %)

30.00, 3.33 Ref 63*
28.30, 5.00 Ref 63*
26.67, 6.67 Ref 63*
23.33, 10.00 Ref 63*
20.00, 13.33 Ref 63*

Boron Magnesium Aluminium - 2

Magnesium, Aluminium (at %)
- 30.00, 3.33 Ref 232*
- 26.67, 6.67 Ref 232*
- 20.00, 13.33 Ref 232*

Resistivity, ohm m × 10^{-8}

Temperature, K

Boron Magnesium Aluminium Lithium

Magnesium, Aluminium, Lithium (at %)
- 30.00, 1.67, 1.67 Ref 62*
- 26.67, 3.33, 3.33 Ref 62*
- 23.33, 5.00, 5.00 Ref 62*
- 20.00, 6.67, 6.67 Ref 62*

Resistivity, ohm m × 10^{-8}

Temperature, K

Boron Magnesium Aluminium Zinc

Magnesium, Aluminium, Zinc (at %)
- 30.00, 1.67, 1.67 Ref 63*
- 26.67, 3.33, 3.33 Ref 63*
- 23.33, 5.00, 5.00 Ref 63*
- 20.00, 6.67, 6.67 Ref 63*
- 13.33, 10.00, 10.00 Ref 63*

Boron Magnesium Carbon

Resistivity, ohm m × 10⁻⁸

Magnesium, Carbon (at %)
33.33, 3.33 Ref 113*
33.33, 6.67 Ref 113*

Temperature, K

Boron Nickel Carbon Holmium

Nickel, Carbon, Holmium (at %)

33.33, 16.67, 16.67 Ref 218*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Boron Silicon Erbium

Silicon, Erbium (at %)

4.26, 2.13 Ref 46*

Resistivity, ohm m × 10^{-8}

Temperature, K

Boron Silicon Terbium

Silicon, Terbium (at %)

4.26, 2.13 Ref 46*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Boron Silicon Ytterbium

Silicon, Ytterbium (at %)

4.26, 2.13 Ref 46*

Resistivity, ohm m × 10^{-8}

Temperature, K

Carbon Hydrogen Nitrogen Selenium
Sulphur Chlorine

Hydrogen, Nitrogen, Selenium, Sulphur, Chlorine (at %)
17.65, 17.65, 11.76, 11.76, 5.88, MSG Ref 158*
17.65, 17.65, 11.76, 11.76, 5.88, OSG Ref 158*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Carbon Selenium Hydrogen Nitrogen Chlorine

Selenium, Hydrogen, Nitrogen, Chlorine (at %)
—⊟— 23.53, 17.65, 17.65, 5.88, MSG Ref 158*

Resistivity, ohm m × 10^{-8}

Temperature, K

Carbon Silicon Boron

Silicon, Boron (at %)
- ⊖— 49.38, 0.99 Ref 48*
- ⊟— 49.27, 1.95 Ref 48*
- ◇— 41.67, 13.33 Ref 48*
- ✕— 36.36, 21.82 Ref 48*
- +— 33.33, 26.67 Ref 48*

Resistivity, ohm m × 10^{-8}

Temperature, K

Carbon Silicon Germanium

Silicon, Germanium (at %)
—⊟— 29.88, 0.23 Ref 148*
—⊡— 29.81, 0.47 Ref 148*
—◇— 29.59, 1.20 Ref 148*
—✕— 29.20, 2.51 Ref 148*
—+— 28.31, 5.47 Ref 148*
—△— 25.94, 13.38 Ref 148*

Carbon Silicon Nickel

Silicon, Nickel (at %)
— ⊖ — 29.91, 0.14 Ref 150*
— ⊟ — 29.86, 0.29 Ref 150*
— ◇ — 29.78, 0.58 Ref 150*
— ✕ — 29.51, 1.49 Ref 150*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Carbon Sulphur Hydrogen Nitrogen Chlorine

Sulphur, Hydrogen, Nitrogen, Chlorine (at %)
23.53, 17.65, 17.65, 5.88, OSG Ref 158*

Resistivity, ohm m × 10⁻³

Temperature, K

Carbon Ytterbium

Ytterbium (at %)

14.29 Ref 156*

Resistivity, ohm m × 10^{-8}

Temperature, K

Chromium Gallium

Gallium (at %)
- 0.65 Ref 20*
- 1.20 Ref 20*
- 1.40 Ref 20*
- 1.68 Ref 20*

Resistivity, ohm m × 10^{-8}

Temperature, K

Chromium Vanadium Gallium

Vanadium, Gallium (at %)

—⊖— 4.15, 1.15 Ref 20*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Copper - 1

Resistivity, ohm m × 10⁻⁸ vs Temperature, K

RM5, NIST, Ref 6*

Copper - 2

Resistivity, ohm m × 10⁻⁸ (vertical axis)

Temperature, K (horizontal axis)

Legend:
○ Nanocrystalline, 100–200 nm Ref 121*
□ Polycrystalline, Ref 124*

Gadolinium

99.9%, Ref 64*

Resistivity, ohm m × 10^{-8}

Temperature, K

Gadolinium Lanthanum

Resistivity, ohm m × 10⁻⁸

Temperature, K

Lanthanum (at %)

15.00 Ref 65*
25.00 Ref 65*
50.00 Ref 65*

Germanium Cobalt Europium

Cobalt, Europium (at %)

31.97, 6.80 Ref 165*

Germanium Cobalt Praseodymium

Cobalt, Praseodymium (at %)

30.00, 20.00 Ref 233*

Germanium Platinum Lanthanum

Platinum, Lanthanum (at %)

⊖— 23.53, 5.88 Ref 214*

Resistivity, ohm m × 10^{-8}

Temperature, K

Indium Selenium Holmium

Selenium, Holmium (at %)
— ○ — 49.94, 0.12 Ref 40*
— □ — 49.38, 1.24 Ref 40*

Resistivity, ohm m × 10^{-8}

Temperature, K

Iron - Linear - 1

99.99% CFE Ref 55*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Iron - Logarithmic - 2

99.99% CFE Ref 55*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Iron - Crystalline - 3

Resistivity, ohm m × 10⁻⁸

Temperature, K

—⊖— Nanocrystalline 100–200 nm Ref 121*
—▱— Polycrystalline Ref 122*

Iron Lanthanum Oxygen Phosphorus

Lanthanum, Oxygen, Phosphorus (at %)
25.00, 25.00, 25.00 Ref 200*

Iron Phosphorus Uranium

Phosphorus, Uranium (at %)
33.33, 9.52 Ref 171*

Resistivity, ohm m × 10^{-8}

Temperature, K

Iron Selenium

Resistivity, ohm m × 10⁻⁸

Selenium (at %)

46.81 Ref 143*

Temperature, K

Iron Tellurium Sulphur

Tellurium, Sulphur (at %)

45.00, 5.00 Ref 179*
40.00, 10.00 Ref 179*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Lanthanum Nitrogen Boron Nickel

Nitrogen, Boron, Nickel (at %)
- ⊖ 27.23, 20.79, 20.79 Ref 204*
- ⊟ 27.91, 20.60, 20.60 Ref 204*
- ◇ 28.35, 20.47, 20.47 Ref 204*
- ✕ 28.93, 20.30, 20.30 Ref 204*
- + 29.44, 20.16, 20.16 Ref 204*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Lanthanum Rhodium Tin

Lithium Aluminium - 1

Aluminium (at %)
- 3.71 Ref 147*
- 4.33 Ref 147*
- 7.49 Ref 147*
- 10.27 Ref 147*
- 10.63 Ref 147*
- 13.12 Ref 147*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Lithium Aluminium - 2

Aluminium (at %)

⊖	15.66 Ref 147*
⊟	16.27 Ref 147*
◇	18.13 Ref 147*
✕	20.83 Ref 147*
┼	21.63 Ref 147*
△	22.96 Ref 147*
■	26.43 Ref 147*
■	30.89 Ref 147*

Resistivity, ohm m × 10^{-8}

Temperature, K

Magnesium Silicon Tin Bismuth

Silicon, Tin, Bismuth (at %)

16.66, 16.66, 0.03 Ref 68*
16.56, 16.56, 0.08 Ref 68*
16.63, 16.63, 0.25 Ref 68*

Resistivity, ohm m × 10^{-8}

Temperature, K

Molybdenum

Resistivity, ohm m × 10⁻⁸ vs Temperature, K

Legend:
—⊖— Purity = 99.93%, Ref 47*
—⊟— Purity data unavailable, Ref 95*

Nickel Bismuth Antimony

Bismuth, Antimony (at %)

44.00, 6.00 Ref 205*

Resistivity, ohm m × 10^{-8}

Temperature, K

Nickel Boron Magnesium

Boron, Magnesium (at %)

22.27, 9.09 Ref 163*

Nickel Carbon Magnesium

Carbon, Magnesium (at %)

27.27, 18.18 Ref 43*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Niobium

Resistivity, ohm m × 10⁻⁸ (vertical axis)

Temperature, K (horizontal axis)

Legend:
- Purity = 99.9%, Ref 30*
- Purity = 99.9%, Ref 38*
- Purity = 99.9%, Ref 5*
- Purity = 99.999%, Ref 43*
- Purity n/a, Ref 95*

Oxygen Barium Tin Bismuth Antimony

Barium, Tin, Bismuth, Antimony (at %)
19.31, 18.53, 1.39, 0.77 Ref 130*
18.18, 17.45, 3.64, 0.73 Ref 130*

Resistance, ohm

Temperature, K

Barium, Titanium, Lanthanum (at %)

- ⊖ 19.94, 19.94, 0.30, Ref 97*
- ⊟ 19.88, 19.88, 0.60, Ref 97*
- ⬦ 19.82, 19.82, 0.90, Ref 97*
- ✕ 19.70, 19.70, 1.50, Ref 97*
- + 19.60, 19.60, 2.00, Ref 97*
- △ 19.50, 19.50, 2.50, Ref 97*
- ● 19.30, 19.30, 3.50, Ref 97*
- ■ 18.00, 18.00, 10.00, Ref 97*

Oxygen Barium Titanium Silicon Lanthanum

Barium, Titanium, Silicon, Lanthanum (at %)
19.92, 19.86, 0.20, 0.04 Ref 145*
20.00, 19.84, 0.20, 0.04 Ref 145*

Oxygen Bismuth Niobium Lanthanum Strontium

Bismuth, Niobium, Lanthanum, Strontium (at %)

14.29, 14.29, 3.57, 3.57 Ref 91*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Bismuth Niobium Strontium

Bismuth, Niobium, Strontium (at %)
14.29, 14.29, 7.14 Ref 91*

Oxygen Bismuth Niobium Strontium Lanthanum

Resistivity, ohm m × 10^{-8}

Temperature, K

Bismuth, Niobium, Strontium, Lanthanum (at %)

14.29, 14.29, 6.43, 0.71 Ref 91*
14.29, 14.29, 5.71, 1.43 Ref 91*
14.29, 14.29, 5.00, 2.14 Ref 91*
14.29, 14.29, 4.29, 2.86 Ref 91*

Oxygen Bismuth Strontium Calcium Bromine

Bismuth, Strontium, Calcium, Bromine (at %)
18.07, 18.07, 9.03, 0.63 Ref 54*

Oxygen Bismuth Strontium Copper

Bismuth, Strontium, Copper (at %)

18.18, 18.18, 9.09 Ref 54*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Oxygen Cadmium Rhenium

Cadmium, Rhenium (at %)
18.18, 18.18 Ref 172*

Oxygen Calcium Titanium Arsenic Iron Magnesium

Calcium, Titanium, Arsenic, Iron, Magnesium (at %)

20.78, 11.69, 10.39, 10.39, 7.79 Ref 173*

Oxygen Cobalt Lanthanum Strontium

Cobalt, Lanthanum, Strontium (at %)
20.00, 13.40, 6.60 Ref 58*

Oxygen Cobalt Lanthanum Strontium Iron

Cobalt, Lanthanum, Strontium, Iron (at %)

19.00, 13.40, 6.60, 1.00 Ref 58*
18.00, 13.40, 6.60, 2.00 Ref 58*
16.00, 13.40, 6.60, 4.00 Ref 58*
14.00, 13.40, 6.60, 6.00 Ref 58*

**Oxygen ($\delta = 0$) Copper Barium Beryllium
Calcium Tellurium Cobalt**

Copper, Barium, Beryllium, Calcium, Tellurium, Cobalt (at %)

19.17, 11.11, 5.56, 5.56, 2.78, 0.28 Ref 226*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

**Oxygen ($\delta = 0$) Copper Barium Calcium
Magnesium Tellurium Cobalt**

Copper, Barium, Calcium, Magnesium Tellurium, Cobalt (at %)
19.17, 11.11, 5.56, 5.56, 2.78, 0.28 Ref 226*

**Oxygen Copper Barium Calcium Magnesium
Thallium - 1**

Copper, Barium, Calcium, Magnesium Thallium (at %)
— ⊙ — 19.44, 11.11, 8.33, 2.78, 2.78 Ref 162*
— ▫ — 19.44, 11.11, 5.56, 5.56, 2.78 Ref 162*

Oxygen ($\delta = 0$) Copper Barium Calcium Tellurium Cobalt

Copper, Barium, Calcium, Tellurium, Cobalt (at %)
—⊖—   19.17, 11.11, 11.11, 2.78, 0.28 Ref 226*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen ($\delta = 0$) Copper Barium Calcium Tellurium Scandium

Copper, Barium, Calcium, Tellurium, Scandium (at %)

— ⊖ — 17.65, 11.76, 11.18, 5.88, 0.59 Ref 227*
— ⊟ — 17.65, 11.76, 10.59, 5.88, 1.18 Ref 227*
— ◇ — 17.64, 11.76, 10.00, 5.88, 1.76 Ref 227*
— ✕ — 17.65, 11.76, 8.24, 5.88, 3.53 Ref 227*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen (δ = 0) Copper Barium Europium

Copper, Barium, Europium (at %)

23.08, 15.38, 7.69 Ref 228*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Oxygen ($\delta = 0$) Copper Barium Europium Manganese

Copper, Barium, Europium, Manganese (at %)

23.03, 15.38, 7.69, 0.12 Ref 228*
22.90, 15.38, 7.69, 0.17 Ref 228*
22.84, 15.38, 7.69, 0.23 Ref 228*
22.62, 15.38, 7.69, 0.46 Ref 228*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen ($\delta = 0$) Copper Barium Gadolinium

Copper, Barium, Gadolinium (at %)
23.13, 15.42, 7.71 Ref 71*
23.08, 15.38, 7.69 Ref 236*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

**Oxygen Copper Barium Gadolinium
Calcium Molybdenum**

Copper, Barium, Gadolinium, Calcium, Molybdenum (at %)

Symbol	Composition
○	23.60, 15.74, 5.51, 1.18, 1.18 Ref 71*
□	23.40, 15.60, 5.07, 1.56, 1.17 Ref 71*
◇	23.51, 15.67, 4.70, 1.96, 1.18 Ref 71*
×	23.75, 15.84, 4.35, 2.38, 1.19 Ref 71*
+	23.83, 15.89, 3.97, 2.78, 1.19 Ref 71*
△	23.92, 15.95, 3.59, 3.19, 1.20 Ref 71*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen ($\delta = 0$) Copper Barium Gadolinium Molybdenum

Copper, Barium, Gadolinium, Molybdenum (at %)

- ⊖ 23.17, 15.44, 7.34, 0.39 Ref 71*
- ⊟ 23.24, 15.49, 6.97, 0.77 Ref 71*
- ◇ 23.33, 15.55, 6.61, 1.17 Ref 71*
- ✕ 23.42, 15.61, 6.25, 1.56 Ref 71*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

**Oxygen Copper Barium Gadolinium
Molybdenum Calcium**

Copper, Barium, Gadolinium, Molybdenum, Calcium (at %)

23.72, 15.81, 6.32, 1.19, 0.40 Ref 71*
23.68, 15.79, 5.92, 1.18, 0.79 Ref 71*

Oxygen (δ = 0) Copper Barium Gadolinium Praseodymium - 1

Copper, Barium, Gadolinium, Praseodymium (at %)
23.08, 15.00, 7.69, 0.39 Ref 236*
23.08, 14.62, 7.69, 0.77 Ref 236*
23.08, 14.23, 7.69, 1.15 Ref 236*

Resistivity, ohm m $\times$ 10^{-8}

Temperature, K

Resistivity, ohm m × 10⁻⁸ vs Temperature, K

Oxygen ($\delta = 0$) Copper Barium Gadolinium Praseodymium - 2

Copper, Barium, Gadolinium, Praseodymium (at %)

23.08, 15.39, 7.31, 0.39 Ref 236*
23.08, 15.39, 6.92, 0.77 Ref 236*
23.08, 15.39, 6.54, 1.15 Ref 236*

Oxygen ($\delta = 0$) Copper Barium Neodymium

Copper, Barium, Neodymium (at %)

23.08, 15.38, 7.69 Ref 221*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen ($\delta = 0$) Copper Barium Neodymium Lanthanum

Copper, Barium, Neodymium, Lanthanum (at %)

23.08, 15.00, 7.69, 0.38 Ref 222*
23.08, 13.85, 7.69, 1.54 Ref 222*
23.08, 13.08, 7.69, 2.31 Ref 222*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen Copper Barium Praseodymium Silver

Copper, Barium, Praseodymium, Silver (at %)
— ◦ — 23.03, 15.35, 7.68, 0.20 Ref 127*
— □ — 23.01, 15.34, 7.67, 0.28 Ref 127*
— ◇ — 22.98, 15.32, 7.66, 0.40 Ref 127*
— × — 22.93, 15.29, 7.64, 0.62 Ref 127*
— + — 22.88, 15.25, 7.63, 0.85 Ref 127*
— △ — 22.83, 15.22, 7.61, 1.09 Ref 127*
— ■ — 22.77, 15.18, 7.59, 1.34 Ref 127*

Oxygen Copper Barium Praseodymium Yttrium

Copper, Barium, Praseodymium, Yttrium (at %)
23.08, 15.38, 6.92, 0.77 Ref 127*
23.08, 15.38, 6.15, 1.54 Ref 127*
23.08, 15.38, 5.38, 2.31 Ref 127*
23.08, 15.38, 4.62, 3.08 Ref 127*
23.08, 15.38, 3.85, 3.85 Ref 127*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Copper Barium Yttrium

Copper, Barium, Yttrium (at %)
— ⊖ —   26.67, 13.33, 6.67 Ref 37*
— ☐ —   23.08, 15.38, 7.69 Ref 127*
— ◇ —   23.08, 15.38, 7.69 Ref 192*

Oxygen Copper Barium Yttrium Gallium

Resistivity, ohm m × 10⁻⁸ (y-axis)

Temperature, K (x-axis)

Copper, Barium, Yttrium, Gallium (at %)

26.67, 13.33, 5.33, 1.33 Ref 225*
26.67, 13.33, 6.00, 0.67 Ref 225*
26.67, 13.33, 6.33, 0.33 Ref 225*

Oxygen Copper Barium Yttrium Phosphorus

Copper, Barium, Yttrium, Phosphorus (at %)

22.64, 15.24, 7.62, 0.23 Ref 192*
22.21, 15.11, 7.55, 0.45 Ref 192*
22.78, 14.97, 7.49, 0.67 Ref 192*
21.36, 14.84, 7.42, 0.89 Ref 192*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Copper Barium Yttrium Praseodymium

Copper, Barium, Yttrium, Praseodymium (at %)

23.08, 15.38, 4.62, 3.08 Ref 127*
23.08, 15.38, 6.15, 1.54 Ref 127*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Oxygen Copper Barium Yttrium Scandium

Copper, Barium, Yttrium, Scandium (at %)
- 26.67, 13.33, 5.33, 1.33 Ref 225*
- 26.67, 13.33, 6.00, 0.67 Ref 225*
- 26.67, 13.33, 6.33, 0.33 Ref 225*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen Copper Bismuth Calcium Strontium

Copper, Bismuth, Calcium, Strontium (at %)

15.79, 10.53, 10.53, 10.53 Ref 54*

**Oxygen Copper Bismuth Calcium
Strontium Bromine**

Copper, Bismuth, Calcium, Strontium, Bromine (at %)
15.63, 10.42, 10.42, 10.42, 0.99 Ref 54*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Oxygen (δ = 0) Copper Calcium Barium Magnesium Thallium

Copper, Calcium, Barium, Magnesium, Thallium (at %)
- 21.15, 11.54, 7.69, 3.85, 1.92, AP, Ref 161*
- 21.15, 11.54, 7.69, 3.85, 1.92, OA, Ref 161*
- 21.15, 7.69, 7.69, 7.69, 1.92, AP, Ref 161*
- 21.15, 7.69, 7.69, 7.69, 1.92, OA, Ref 161*

Oxygen ($\delta = 0$) Copper Calcium Barium Thallium

Copper, Calcium, Barium, Thallium (at %)
—⊟— 20.69, 13.79, 9.20, 2.30 Ref 126*

Oxygen Copper Rhodium

Copper, Rhodium (at %)
25.00, 25.00 Ref 49*

Oxygen Copper Rhodium Magnesium

Copper, Rhodium, Magnesium (at %)
25.00, 23.75, 1.25 Ref 49*
25.00, 20.00, 5.00 Ref 49*

Oxygen Copper Strontium

Copper, Strontium (at %)

30.38, 17.72 Ref 69*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Oxygen Copper Strontium Cobalt

Copper, Strontium, Cobalt (at %)
- 29.77, 17.72, 0.61 Ref 69*
- 28.56, 17.72, 1.82 Ref 69*
- 27.34, 17.72, 3.04 Ref 69*
- 26.13, 17.72, 4.25 Ref 69*
- 24.91, 17.72, 5.47 Ref 69*

Oxygen Copper Strontium Erbium Niobium Cerium

Copper, Strontium, Erbium, Niobium, Cerium (at %)
—⊕—   11.76, 11.76, 8.82, 5.88, 2.94 Ref 219*

Oxygen Copper Strontium Gadolinium Ruthenium

Copper, Strontium, Gadolinium, Ruthenium (at %)

14.29, 14.29, 7.14, 7.14 Ref 131*

Resistivity, ohm m × 10⁻⁸

Temperature, K

**Oxygen Copper Strontium Holmium
Niobium Cerium**

Copper, Strontium, Holmium, Niobium, Cerium (at %)
⊖——— 11.76, 11.76, 8.82, 5.88, 2.94 Ref 219*

**Oxygen Copper Strontium Ruthenium
Gadolinium Dysprosium**

Copper, Strontium, Ruthenium, Gadolinium, Dysprosium (at %)

14.29, 14.29, 7.14, 4.29, 2.86 Ref 131*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Copper Strontium Ruthenium Gadolinium Yttrium

Copper, Strontium, Ruthenium, Gadolinium, Yttrium (at %)

14.29, 14.29, 7.14, 6.43, 0.71 Ref 131*

Resistivity, ohm m × 10⁻⁸

Temperature, K

**Oxygen Copper Strontium Terbium
Niobium Cerium**

Copper, Strontium, Terbium, Niobium, Cerium (at %)

11.76, 11.76, 8.82, 5.88, 2.94 Ref 219*

Oxygen Europium Zirconium

Europium, Zirconium (at %)
20.00, 20.00 Ref 140*

Oxygen Iron Barium Antimony

Iron, Barium, Antimony (at %)

37.34, 3.13, 0.16 Ref 84*
37.19, 3.13, 0.31 Ref 84*
36.88, 3.13, 0.63 Ref 84*

Oxygen Iron Cobalt Lithium Antimony

Iron, Cobalt, Lithium, Antimony (at %)
- ○ 30.00, 5.71, 5.71, 1.43 Ref 52*
- □ 27.14, 11.43, 2.86, 1.43 Ref 52*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Iron Lithium Cobalt Antimony

Iron, Lithium, Cobalt, Antimony (at %)

31.43, 7.14, 2.86, 1.43 Ref 52*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Lanthanum Chromium Manganese Calcium

Lanthanum, Chromium, Manganese, Calcium (at %)
14.00, 10.00, 10.00, 6.00 Ref 50*

Oxygen Lanthanum Copper Magnesium Strontium

Lanthanum, Copper, Magnesium, Strontium (at %)
- ○ 26.43, 11.43, 2.86, 2.14 Ref 44*
- □ 26.43, 10.00, 4.29, 2.14 Ref 44*

Resistivity, ohm m × 10⁻⁸ — $Resistivity, ohm\ m \times 10^{-8}$

Temperature, K

Oxygen Lanthanum Copper Strontium Nickel

Resistivity, ohm m × 10^{-8}

Temperature, K

Lanthanum, Copper, Strontium, Nickel (at %)

27.14, 14.00, 1.43, 0.29 Ref 51*
27.14, 13.71, 1.43, 0.57 Ref 51*
27.14, 13.43, 1.43, 0.86 Ref 51*

Oxygen Lanthanum Copper Strontium Titanium - 1

Resistivity, ohm m × 10⁻⁸ vs Temperature, K

Lanthanum, Copper, Strontium, Titanium (at %)
26.43, 14.00, 2.14, 0.29 Ref 13*
26.43, 13.70, 2.14, 0.57 Ref 13*
26.43, 13.40, 2.14, 0.86 Ref 13*

Oxygen Lanthanum Copper Strontium Zinc

Lanthanum, Copper, Strontium, Zinc (at %)

27.14, 13.71, 1.43, 0.57 Ref 51*
27.14, 13.14, 1.43, 1.14 Ref 51*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Oxygen Lanthanum Nickel Antimony

Lanthanum, Nickel, Antimony (at %)

- 20.00, 19.00, 1.00 Ref 60*
- 20.00, 17.00, 3.00 Ref 60*
- 20.00, 15.00, 5.00 Ref 60*
- 20.00, 14.00, 6.00 Ref 60*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen Lanthanum Rhodium Nickel

Lanthanum, Rhodium, Nickel (at %)
20.00, 19.00, 1.00 Ref 33*
20.00, 18.00, 4.00 Ref 33*
20.00, 16.00, 4.00 Ref 33*
20.00, 14.00, 6.00 Ref 33*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Oxygen Lanthanum Strontium Copper Titanium

Lanthanum, Strontium, Copper, Titanium (at %)
17.86, 10.71, 10.00, 4.29 Ref 13*
15.00, 13.57, 8.57, 5.71 Ref 13*

Oxygen Manganese Lanthanum Calcium - 1

Manganese, Lanthanum, Calcium (at %)
20.00, 13.00, 7.00 Ref 57*
20.00, 15.00, 5.00 Ref 76*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Manganese Lanthanum Calcium - 2

Manganese, Lanthanum, Calcium (at %)

⊖ 20.00, 14.00, 6.00 Ref 24*
⊟ 20.00, 14.00, 6.00 Ref 50*

Resistivity, ohm m × 10⁻⁸

Temperature, K

**Oxygen Manganese Lanthanum
Calcium Aluminium**

Manganese, Lanthanum, Calcium, Aluminium (at %)

○— 19.80, 15.00, 5.00, 0.20 Ref 76*
□— 19.40, 15.00, 5.00, 0.60 Ref 76*
◇— 19.20, 15.00, 5.00, 0.80 Ref 76*
×— 19.00, 15.00, 5.00, 1.00 Ref 76*

Oxygen Manganese Lanthanum Calcium Chromium

Resistivity, ohm m × 10⁻⁸

Temperature, K

Manganese, Lanthanum, Calcium, Chromium (at %)

19.00, 14.00, 6.00, 1.00 Ref 50*
18.00, 14.00, 6.00, 2.00 Ref 50*
17.00, 14.00, 6.00, 3.00 Ref 50*

Oxygen Manganese Lanthanum Calcium Gallium

Manganese, Lanthanum, Calcium, Gallium (at %)
19.80, 14.00, 6.00, 0.20 Ref 70*
19.60, 14.00, 6.00, 0.40 Ref 70*
19.20, 14.00, 6.00, 0.80 Ref 70*
18.00, 14.00, 6.00, 2.00 Ref 70*

Oxygen Manganese Lanthanum Calcium Iron

Manganese, Lanthanum, Calcium, Iron (at %)

◯	19.80, 13.00, 7.00, 0.20 Ref 57*
▢	19.60, 13.00, 7.00, 0.40 Ref 57*
◇	19.40, 13.00, 7.00, 0.60 Ref 57*
✕	19.00, 13.00, 7.00, 1.00 Ref 57*
+	18.60, 13.00, 7.00, 1.40 Ref 57*
△	18.40, 13.00, 7.00, 1.60 Ref 56*
▪	18.00, 13.00, 7.00, 2.00 Ref 56*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Manganese Lanthanum Calcium Silver Barium

Resistivity, ohm m × 10^{-8} vs Temperature, K

Manganese, Lanthanum, Calcium, Silver, Barium (at %)
19.23, 13.46, 3.85, 3.85, 1.92 Ref 28*

Oxygen Manganese Lanthanum Calcium Tellurium

Manganese, Lanthanum, Calcium, Tellurium (at %)
20.00, 10.00, 9.00, 1.00 Ref 17*
20.00, 10.00, 8.00, 2.00 Ref 17*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Manganese Lanthanum Calcium Titanium - 1

Manganese, Lanthanum, Calcium, Titanium (at %)

—⊖—   19.80, 14.00, 6.00, 0.20 Ref 24*
—☐—   19.40, 14.00, 6.00, 0.60 Ref 24*
—◇—   19.00, 14.00, 6.00, 1.00 Ref 24*
—✕—   18.60, 14.00, 6.00, 1.40 Ref 24*
—+—   18.00, 14.00, 6.00, 2.00 Ref 24*
—△—   16.00, 14.00, 6.00, 4.00 Ref 24*
—■—   14.00, 14.00, 6.00, 6.00 Ref 24*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Manganese Lanthanum Lead

Manganese, Lanthanum, Lead (at %)
20.00, 10.00, 10.00 Ref 23*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Manganese Lanthanum Lead Silver

Manganese, Lanthanum, Lead, Silver (at %)
18.18, 9.09, 9.09, 9.09 Ref 12*
19.61, 9.80, 9.80, 1.96 Ref 23*

Oxygen Manganese Lanthanum Potassium

Manganese, Lanthanum, Potassium (at %)
- 20.00, 19.00, 1.00 Ref 29*
- 20.00, 18.00, 2.00 Ref 29*
- 20.00, 17.00, 3.00 Ref 29*
- 20.00, 13.40, 6.60 Ref 34*

Oxygen Manganese Lanthanum Rubidium

Manganese, Lanthanum, Rubidium (at %)
—⊖— 20.00, 13.40, 6.60 Ref 34*

Resistivity, ohm m × 10^{-8}

1.2×10^7

1×10^7

8×10^6

6×10^6

4×10^6

50   100   150   200   250   300

Temperature, K

**Oxygen Manganese Lanthanum Silver
Calcium Barium**

Manganese, Lanthanum, Silver, Calcium, Barium (at %)
18.52, 12.96, 7.41, 3.70, 1.85 Ref 28*
17.86, 12.50, 10.71, 3.57, 1.79 Ref 28*

Oxygen Manganese Lanthanum Sodium

Manganese, Lanthanum, Sodium (at %)

20.00, 13.40, 6.60 Ref 34*

Resistivity, ohm m × 10⁻³

Temperature, K

Oxygen Manganese Lanthanum Zinc

Manganese, Lanthanum, Zinc (at %)

19.54, 17.27, 1.50 Ref 8*

**Oxygen Manganese Silver Lanthanum
Barium Calcium**

Manganese, Silver, Lanthanum, Barium, Calcium (at %)
17.24, 13.79, 12.07, 2.59, 2.59 Ref 28*

**Oxygen Manganese Silver Lanthanum
Calcium Barium**

Manganese, Silver, Lanthanum, Calcium, Barium (at %)

17.24, 13.79, 12.07, 3.45, 1.72 Ref 28*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Manganese Strontium Praseodymium

Manganese, Strontium, Praseodymium (at %)
20.00, 11.2, 8.80 Ref 133*

**Oxygen Manganese Strontium
Praseodymium Chromium**

Manganese, Strontium, Praseodymium, Chromium (at %)
—⊖— 19.60, 11.00, 9.00, 0.40 Ref 133*
—□— 19.20, 10.80, 9.20, 0.80 Ref 133*
—◇— 18.80, 10.60, 9.40, 1.20 Ref 133*
—✕— 18.40, 10.40, 9.60, 1.60 Ref 133*

Oxygen Manganese Strontium Praseodymium Lanthanum

Manganese, Strontium, Praseodymium, Lanthanum (at %)

16.67, 16.67, 5.83, 2.50 Ref 36*

Oxygen Palladium Calcium Copper Sodium

Palladium, Calcium, Copper, Sodium (at %)
31.25, 8.75, 6.25, 3.75 Ref 83*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Rhodium Calcium Sodium

Rhodium, Calcium, Sodium (at %)

28.57, 10.71, 3.57 Ref 73*

Oxygen Rhodium Sodium Calcium

Rhodium, Sodium, Calcium (at %)

28.57, 10.71, 3.57 Ref 73*

Oxygen Samarium Copper Cerium

Samarium, Copper, Cerium (at %)
26.43, 14.2, 2.14 Ref 11*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Oxygen Samarium Copper Selenium Cerium

Samarium, Copper, Selenium, Cerium (at %)
- 25.69, 13.89, 2.78, 2.08 Ref 11*
- 25.34, 13.70, 4.11, 2.05 Ref 11*
- 25.00, 13.51, 5.41, 2.03 Ref 11*
- 24.67, 13.33, 6.67, 2.00 Ref 11*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen Strontium Arsenic Iron Scandium

Strontium, Arsenic, Iron, Scandium (at %)
25.00, 12.50, 12.50, 12.50 Ref 181*

Resistivity, ohm m × 10⁻⁸ (y-axis)

Temperature, K (x-axis)

Oxygen Strontium Arsenic Nickel Scandium

Strontium, Arsenic, Nickel, Scandium (at %)
25.00, 12.50, 12.50, 12.50 Ref 182*

Oxygen Strontium Iron Phosphorus Scandium

Strontium, Iron, Phosphorus, Scandium (at %)

25.00, 12.50, 12.50, 12.50 Ref 201*

Oxygen Strontium Nickel Phosphorus Scandium

Strontium, Nickel, Phosphorus, Scandium (at %)
25.00, 12.50, 12.50, 12.50 Ref 182*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Strontium Rhodium

Resistivity, ohm m × 10⁻⁸ (y-axis)

Temperature, K (x-axis)

Strontium, Rhodium (at %)

28.57, 14.29 Ref 75*
25.00, 16.67 Ref 74*
23.53, 17.64 Ref 75*

**Oxygen Titanium Barium Calcium
Silicon Lanthanum**

Titanium, Barium, Calcium, Silicon, Lanthanum (at %)
19.92, 15.70, 3.98, 0.20. 0.04 Ref 145*
19.90, 15.78, 3.98, 0.20. 0.04 Ref 145*
19.88, 15.86, 3.98, 0.20. 0.04 Ref 145*
19.86, 15.95, 3.97, 0.20. 0.04 Ref 145*
19.84, 16.03, 3.97, 0.20. 0.04 Ref 145*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Titanium Barium Lanthanum

Titanium, Barium, Lanthanum (at %)
T_s = Sintered temperature

⊖	20.16, 19.71, 0.049, Ref 98*
⊟	20.16, 19.46, 0.30, Ref 98*
◇	20.16, 19.46, 0.30, Ref 98*
×	20.16, 19.46, 0.30, Ref 98*
+	20.16, 18.77, 0.99, Ref 98*

T_s = 1589 K

T_s = 1490 K

T_s = 1553 K

T_s = 1650 K

T_s = 1290 K

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Titanium Barium Strontium

Titanium, Barium, Strontium (at %)
20.00, 18.00, 2.00 Ref 142*

Oxygen Titanium Strontium Yttrium

Titanium, Strontium, Yttrium (at %)
—⊖—   20.00, 18.00, 2.00, Hot pressed 1473 K, 1 h, Ref 144*
—⊟—   20.00, 18.00, 2.00, Hot pressed 1673 K, 2 h, Ref 144*

Resistivity, ohm m × 10⁻⁸ (y-axis)

Temperature, K (x-axis)

**Oxygen Tungsten Phosphorus Molybdenum
Potassium**

Tungsten, Phosphorus, Molybdenum, Potassium (at %)

17.25, 5.80, 3.04, 1.45, b axis Ref 153*

Resistivity, ohm m $\times$ 10^{-8}

Temperature, K

Oxygen Tungsten Phosphorus Potassium Cobalt

Tungsten, Phosphorus, Potassium, Cobalt (at %)

⊝ 19.66, 6.55, 1.64, 0.07, b axis Ref 153*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen Tungsten Phosphorus Potassium Molybdenum - 1

Tungsten, Phosphorus, Potassium, Molybdenum (at %)

19.86, 5.80, 1.45, 0.43, b axis Ref 153*
19.42, 5.80, 1.45, 0.87, b axis Ref 153*
18.99, 5.80, 1.45, 1.30, b axis Ref 153*

Oxygen Tungsten Phosphorus Potassium Molybdenum - 2

Tungsten, Phosphorus, Potassium, Molybdenum (at %)

18.26, 6.56, 1.64, 1.41, b axis Ref 153*

**Oxygen Tungsten Phosphorus Potassium
Molybdenum - 3**

Tungsten, Phosphorus, Potassium, Molybdenum (at %)
18.61, 6.56, 1.64, 1.07, b axis Ref 153*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen Tungsten Phosphorus Potassium Rubidium

Tungsten, Phosphorus, Potassium, Rubidium (at %)

—◻— 19.74, 6.58, 1.09, 0.23, b axis Ref 153*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Tungsten Phosphorus Potassium Tin Iron

Tungsten, Phosphorus, Potassium, Tin, Iron (at %)
19.64, 6.55, 1.64, 0.08, 0.07, b axis Ref 153*

Oxygen Vanadium Tungsten

Vanadium, Tungsten (at %)

33.33, 0.017 Ref 78*
33.31, 0.083 Ref 78*
33.32, 0.033 Ref 78*
33.28, 0.17 Ref 78*

Oxygen Zinc Calcium Barium Copper Thallium

Zinc, Calcium, Barium, Copper, Thallium (at %)

16.02, 13.73, 9.15, 4.58, 2.29 Ref 126*

Platinum (Logarithmic)

99.99% Ref 55*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Platinum Uranium Yttrium

Resistivity, ohm m × 10⁻⁸ (vertical axis)

Temperature, K (horizontal axis)

Uranium, Yttrium (at %)
24.98, 0.012 Ref 41*
24.94, 0.065 Ref 41*
24.96, 0.040 Ref 41*
24.91, 0.093 Ref 41*
24.87, 0.130 Ref 41*

Rhodium Sulphur

Sulphur (at %)

46.88 Ref 180*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Rhodium Sulphur Iridium

Resistivity, ohm m $\times 10^{-8}$ vs Temperature, K

Sulphur, Iridium (at %)

46.88, 3.13 Ref 180*
46.88, 6.25 Ref 180*

Samarium

99.9% purity, Ref 141*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Selenium Copper Aluminium Zinc

Copper, Aluminium, Zinc (at %)

25.48, 10.82, 0.39 Ref 151*

Selenium Copper Germanium

Copper, Germanium (at %)

33.33, 16.67 Ref 35*

Resistivity, ohm m × 10^{-8}

Temperature, K

Selenium Molybdenum Lanthanum

Molybdenum, Lanthanum (at %)

40.16, 6.29 Ref 85*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Silicon Lanthanum Rhenium

Lanthanum, Rhenium (at %)

20.00, 20.00 Ref 186*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Silicon Zirconium Copper

Zirconium, Copper (at %)

28.57, 14.29 Ref 9*

Resistivity, ohm m × 10⁻⁸ (y-axis)

Temperature, K (x-axis)

Silver Chromium

Chromium (at %)
— ⊖ — 0.1 Ref 129*
— ☐ — 0.2 Ref 129*
— ◇ — 0.3 Ref 129*
— ✕ — 0.4 Ref 129*

Resistivity, ohm m × 10^{-8}

Temperature, K

Sulphur Molybdenum Lanthanum

Molybdenum, Lanthanum (at %)

40.00, 6.67 Ref 85*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Sulphur Tantulum Copper

Tantulum, Copper (at %)

33.00, 0.99 Ref 166*

Resistivity, ohm m × 10^{-8}

Temperature, K

Sulphur Vanadium Iron

Sulphur Yttrium Aluminium

Yttrium, Aluminium (at %)

32.89, 1.33, Heating Ref 134*
32.89, 1.33, Cooling Ref 134*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Titanium Vanadium Aluminium Chromium Tin

Vanadium, Aluminium, Chromium, Tin (at %)

14.16, 5.36, 2.78, 1.22 Ref 168*

6.2   Electrical resistivity as a function of temperature and pressure

Arsenic Iron Barium - 2

Iron, Barium (at %)
- ⊖ 40.00, 20.00, $P = 0$ GPa, Ref 195*
- ⊡ 40.00, 20.00, $P = 2.5$ GPa, Ref 195*
- ◇ 40.00, 20.00, $P = 3.0$ GPa, Ref 195*

Resistivity, ohm m × 10^{-8}

Temperature, K

Arsenic Iron Barium Potassium

Iron, Barium, Potassium (at %)

- ⊖ 40.00, 12.00, 8.00, P = 1.00 GPa, Ref 196*
- ⊟ 40.00, 12.00, 8.00, P = 2.00 GPa, Ref 196*
- ◇ 40.00, 12.00, 8.00, P = 4.00 GPa, Ref 196*
- ✕ 40.00, 12.00, 8.00, P = 6.00 GPa, Ref 196*
- + 40.00, 12.00, 8.00, P = 9.00 GPa, Ref 196*
- △ 40.00, 12.00, 8.00, P = 13.00 GPa, Ref 196*
- ■ 40.00, 12.00, 8.00, P = 17.00 GPa, Ref 196*

Resistivity, ohm m × 10^{-8}

Temperature, K

Arsenic Iron Europium

Iron, Europium (at %)

—⊖—	40.00, 20.00 P = 2.38 GPa, Ref 223*
—⊟—	40.00, 20.00 P = 2.46 GPa, Ref 223*
—◇—	40.00, 20.00 P = 2.55 GPa, Ref 223*
—✕—	40.00, 20.00 P = 2.77 GPa, Ref 223*
—+—	40.00, 20.00 P = 3.00 GPa, Ref 223*

Resistivity, ohm m $\times$ 10^{-8}

Temperature, K

Arsenic Iron Lanthanum Oxygen Fluorine - 1

Iron, Lanthanum, Oxygen, Fluorine (at %)
25.00, 25.00, 21.50, 3.50, P = 0 GPa, Ref 209*
25.00, 25.00, 21.50, 3.50, P = 0.92 GPa, Ref 209*
25.00, 25.00, 21.50, 3.50, P = 1.54 GPa, Ref 209*

**Arsenic Iron Lanthanum Oxygen
Fluorine - 2**

Iron, Lanthanum, Oxygen, Fluorine (at %)

25.00, 25.00, 21.50, 3.50, P = 2.00 GPa, Ref 209*
25.00, 25.00, 21.50, 3.50, P = 3.00 GPa, Ref 209*
25.00, 25.00, 21.50, 3.50, P = 4.50 GPa, Ref 209*
25.00, 25.00, 21.50, 3.50, P = 6.00 GPa, Ref 209*
25.00, 25.00, 21.50, 3.50, P = 7.50 GPa, Ref 209*
25.00, 25.00, 21.50, 3.50, P = 9.00 GPa, Ref 209*
25.00, 25.00, 21.50, 3.50, P = 12.00 GPa, Ref 209*

Resistivity, ohm m × 10^{-8}

Temperature, K

Arsenic Iron Neodymium Oxygen

Iron, Neodymium, Oxygen (at %)
27.78, 27.78, 16.67, $P = 0$ GPa, Ref 217*
27.78, 27.78, 16.67, $P = 1.0$ GPa, Ref 217*
27.78, 27.78, 16.67, $P = 3.0$ GPa, Ref 217*
27.78, 27.78, 16.67, $P = 5.0$ GPa, Ref 217*
27.78, 27.78, 16.67, $P = 7.5$ GPa, Ref 217*
27.78, 27.78, 16.67, $P = 10.0$ GPa, Ref 217*
27.78, 27.78, 16.67, $P = 12.5$ GPa, Ref 217*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Arsenic Rhodium Lanthanum

Rhodium, Lanthanum (at %)
- 23.53, 5.88, P = 0.00 GPa, Ref 199*
- 23.53, 5.88, P = 0.50 GPa, Ref 199*
- 23.53, 5.88, P = 1.00 GPa, Ref 199*
- 23.53, 5.88, P = 1.50 GPa, Ref 199*

Resistivity, ohm m × 10^{-8}

Temperature, K

Beryllium

Resistivity, ohm m × 10⁻⁸ vs Temperature, K

$P = 0.12$ GPa, Ref 15

Erbium

Resistivity, ohm m × 10⁻⁸ vs Temperature, K

P = 0.1 MPa, Ref 94*
P = 50 MPa, Ref 94*
P = 150 MPa, Ref 94*
P = 450 MPa, Ref 94*
P = 750 MPa, Ref 94*
P = 1200 MPa, Ref 94*

Gadolinium - 1

P = 0.4 GPa, Ref 64*
P = 1.0 GPa, Ref 64*
P = 2.1 GPa, Ref 64*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Gadolinium - 2

P = 1.67 GPa, Ref 19*
P = 3.35 GPa, Ref 19*
P = 3.75 GPa, Ref 19*
P = 3.95 GPa, Ref 19*
P = 4.78 GPa, Ref 19*

Iron Selenium Tellurium

Selenium, Tellurium (at %)

25.00, 25.00, *P* = 1.0 GPa, Ref 178*
25.00, 25.00, *P* = 1.3 GPa, Ref 178*
25.00, 25.00, *P* = 1.6 GPa, Ref 178*
25.00, 25.00, *P* = 2.0 GPa, Ref 178*
25.00, 25.00, *P* = 2.5 GPa, Ref 178*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Nickel - 1

Purity 99.99%

P = 0.2 MPa, Ref 237*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Nickel - 2

Resistivity, ohm m × 10⁻⁸ (y-axis)

Temperature, K (x-axis)

P = 2.00 GPa, Ref 137*
P = 4.00 GPa, Ref 137*
P = 5.00 GPa, Ref 137*

Nickel - 3

Legend:
- Nanocrystalline, P = 0.48 GPa, Ref 125*
- Nanocrystalline, P = 0.98 GPa, Ref 125*
- Nanocrystalline, P = 1.47 GPa, Ref 125*
- Nanocrystalline, P = 1.98 GPa, Ref 125*

Y-axis: Resistivity, ohm m $\times$ 10^{-8}

X-axis: Temperature, K

Nickel - 4

- ⊖— 40 nm particles, P = 1.96 GPa, Ref 125*
- ⊟— 50 nm particles, P = 1.96 GPa, Ref 125*
- ⬦— 70 nm particles, P = 1.96 GPa, Ref 125*
- ✕— 100 nm particles, P = 1.96 GPa, Ref 125*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen (δ = 0.26) Copper Barium Praseodymium - 1

Copper, Barium, Praseodymium (at %)

25.23, 14.42, 7.21, *P* = 0 GPa, Ref 193*
25.23, 14.42, 7.21, *P* = 1.0 GPa, Ref 193*
25.23, 14.42, 7.21, *P* = 1.5 GPa, Ref 193*
25.23, 14.42, 7.21, *P* = 2.0 GPa, Ref 193*
25.23, 14.42, 7.21, *P* = 2.5 GPa, Ref 193*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen (δ = 0.64) Copper Barium Praseodymium - 2

Copper, Barium, Praseodymium (at %)

25.58, 14.62, 7.31, *P* = 0 GPa, Ref 193*
25.58, 14.62, 7.31, *P* = 1.0 GPa, Ref 193*
25.58, 14.62, 7.31, *P* = 1.5 GPa, Ref 193*
25.58, 14.62, 7.31, *P* = 2.0 GPa, Ref 193*
25.58, 14.62, 7.31, *P* = 2.5 GPa, Ref 193*
25.58, 14.62, 7.31, *P* = 8.0 GPa, Ref 193*
25.58, 14.62, 7.31, *P* = 10.0 GPa, Ref 193*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen ($\delta = 0$) Copper Barium Praseodymium - 3

Copper, Barium, Praseodymium (at %)

—⊖—	25.73, 14.70, 7.35, $P = 0$ GPa, Ref 193*
—▢—	25.73, 14.70, 7.35, $P = 1.5$ GPa, Ref 193*
—◇—	25.73, 14.70, 7.35, $P = 2.0$ GPa, Ref 193*
—✕—	25.73, 14.70, 7.35, $P = 5.0$ GPa, Ref 193*
—+—	25.73, 14.70, 7.35, $P = 8.0$ GPa, Ref 193*
—△—	25.73, 14.70, 7.35, $P = 10.0$ GPa, Ref 193*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen Copper Barium Yttrium Nickel

Copper, Barium, Yttrium, Nickel (at %)
— ⊖ — 26.65, 13.32, 6.66, 0.067 a axis, P = 0.10 MPa, Ref 118*
— ⊟ — 26.65, 13.32, 6.66, 0.067 a axis, P = 0.61 GPa, Ref 118*
— ◇ — 26.65, 13.32, 6.66, 0.067 a axis, P = 1.00 GPa, Ref 118*
— ✕ — 26.65, 13.32, 6.66, 0.067 a axis, P = 1.29 GPa, Ref 118*
— + — 26.65, 13.32, 6.66, 0.067 a axis, P = 1.57 GPa, Ref 118*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen Manganese Lanthanum

Manganese, Lanthanum (at %)

- *P* = 0, 19.55, 18.72, Ref 22*
- *P* = 0.36 GPa, 19.55, 18.72 Ref 22*
- *P* = 0.65 GPa, 19.55, 18.72 Ref 22*
- *P* = 0.84 GPa, 19.55, 18.72 Ref 22*

Oxygen Manganese Lanthanum Strontium Scandium

Manganese, Lanthanum, Strontium, Scandium (at %)
18.00, 14.00, 6.00, 2.00, 0 *T*, Ref 116*

Temperature, K

Resistance, ohms

Oxygen Manganese Lanthanum Zinc

Manganese, Lanthanum, Zinc (at %)
— ⊖ — $P = 0$, 19.54, 17.27, 1.50 Ref 8*
— ⊡ — $P = 0.52$ GPa, 19.54, 17.27, 1.50 Ref 8*
— ◇ — $P = 0.73$ GPa, 19.54, 17.27, 1.50 Ref 8*
— ✕ — $P = 0.94$ GPa, 19.54, 17.27, 1.50 Ref 8*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen Silver Sulphur - 1

Silver, Sulphur (at %)

- 28.57, 14.29, Heating, $P = 1.14$ GPa, Ref 136*
- 28.57, 14.29, Cooling, $P = 1.14$ GPa, Ref 136*
- 28.57, 14.29, Heating, $P = 1.47$ GPa, Ref 136*
- 28.57, 14.29, Cooling, $P = 1.47$ GPa, Ref 136*
- 28.57, 14.29, Heating, $P = 1.66$ GPa, Ref 136*
- 28.57, 14.29, Cooling, $P = 1.66$ GPa, Ref 136*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen Silver Sulphur - 2

Silver, Sulphur (at %)

—o—	28.57, 14.29, Heating, P = 1.93 GPa, Ref 136*
—□—	28.57, 14.29, Cooling, P = 1.93 GPa, Ref 136*
—◇—	28.57, 14.29, Heating, P = 2.24 GPa, Ref 136*
—×—	28.57, 14.29, Cooling, P = 2.24 GPa, Ref 136*
—+—	28.57, 14.29, Heating, P = 2.43 GPa, Ref 136*
—△—	28.57, 14.29, Cooling, P = 2.43 GPa, Ref 136*
—●—	28.57, 14.29, Heating, P = 4.21 GPa, Ref 136*
—■—	28.57, 14.29, Cooling, P = 4.21 GPa, Ref 136*

Resistivity, ohm m × 10^{-8}

Temperature, K

Oxygen Silver Sulphur Thallium - 1

Silver, Sulphur, Thallium (at %)

—⊖—	14.29, 14.29, 14.29, Heating, *P* = 0.63 GPa, Ref 138*
—⊟—	14.29, 14.29, 14.29, Cooling, *P* = 0.63 GPa, Ref 138*
—◇—	14.29, 14.29, 14.29, Heating, *P* = 0.77 GPa, Ref 138*
—✕—	14.29, 14.29, 14.29, Cooling, *P* = 0.77 GPa, Ref 138*
—+—	14.29, 14.29, 14.29, Heating, *P* = 0.90 GPa, Ref 138*
—△—	14.29, 14.29, 14.29, Cooling, *P* = 0.90 GPa, Ref 138*

Oxygen Silver Sulphur Thallium - 2

Silver, Sulphur, Thallium (at %)

- ⊖ 14.29, 14.29, 14.29, Heating, *P* = 1.04 GPa, Ref 138*
- ⊟ 14.29, 14.29, 14.29, Cooling, *P* = 1.04 GPa, Ref 138*
- ◇ 14.29, 14.29, 14.29, Heating, *P* = 1.17 GPa, Ref 138*
- × 14.29, 14.29, 14.29, Cooling, *P* = 1.17 GPa, Ref 138*
- + 14.29, 14.29, 14.29, Heating, *P* = 1.27 GPa, Ref 138*
- △ 14.29, 14.29, 14.29, Cooling, *P* = 1.27 GPa, Ref 138*

Resistivity, ohm m $\times 10^{-8}$

Temperature, K

Oxygen Silver Sulphur Thallium - 3

Silver, Sulphur, Thallium (at %)

⊖	14.29, 14.29, 14.29, Heating, $P = 1.61$ GPa, Ref 138*
⊟	14.29, 14.29, 14.29, Cooling, $P = 1.61$ GPa, Ref 138*
◇	14.29, 14.29, 14.29, Cooling, $P = 2.43$ GPa, Ref 138*
✕	14.29, 14.29, 14.29, Heating, $P = 3.34$ GPa, Ref 138*
+	14.29, 14.29, 14.29, Cooling, $P = 3.34$ GPa, Ref 138*
△	14.29, 14.29, 14.29, Heating, $P = 4.00$ GPa, Ref 138*
●	14.29, 14.29, 14.29, Cooling, $P = 4.00$ GPa, Ref 138*
■	14.29, 14.29, 14.29, Heating, $P = 4.95$ GPa, Ref 138*
◆	14.29, 14.29, 14.29, Cooling, $P = 4.95$ GPa, Ref 138*

Ruthenium Silicon Uranium - 2

Silicon, Uranium (at %)

40.00, 20.00, *P* = 0.05 GPa, Ref 170*
40.00, 20.00, *P* = 0.50 GPa, Ref 170*
40.00, 20.00, *P* = 0.85 GPa, Ref 170*
40.00, 20.00, *P* = 1.32 GPa, Ref 170*
40.00, 20.00, *P* = 1.55 GPa, Ref 170*

Resistivity, ohm m × 10^{-8}

Temperature, K

Silicon Cerium Iridium

Cerium, Iridium (at %)

20.00, 20.00, P = 1.99 GPa, Ref 215*
20.00, 20.00, P = 2.19 GPa, Ref 215*
20.00, 20.00, P = 2.30 GPa, Ref 215*
20.00, 20.00, P = 2.58 GPa, Ref 215*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Uranium - 2

P = 0.1 MPa, Ref 26*
P = 1.6 GPa, Ref 26*
P = 3.9 GPa, Ref 26*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Ytterbium

P = 2.2 GPa, Ref 21*
P = 4.5 GPa, Ref 21*
P = 9.1 GPa, Ref 21*

Resistivity, ohm m × 10⁻⁸

Temperature, K

Zinc Cobalt Ytterbium

Cobalt, Ytterbium (at %)

- 8.69, 4.35, P = 0.00 GPa, Ref 191*
- 8.69, 4.35, P = 2.00 GPa, Ref 191*
- 8.69, 4.35, P = 4.00 GPa, Ref 191*
- 8.69, 4.35, P = 6.00 GPa, Ref 191*
- 8.69, 4.25, P = 12.00 GPa, Ref 191*

Resistivity, ohm m × 10^{-8}

Temperature, K

Zinc Iridium Ytterbium

Iridium, Ytterbium (at %)

— ⊖ — 8.69, 4.35, *P* = 0.00 GPa, Ref 191*
— ⊟ — 8.69, 4.35, *P* = 2.00 GPa, Ref 191*
— ◇ — 8.69, 4.35, *P* = 4.00 GPa, Ref 191*
— ✕ — 8.69, 4.35, *P* = 6.00 GPa, Ref 191*
— ✛ — 8.69, 4.35, *P* = 12.00 GPa, Ref 191*

Resistivity, ohm m × 10^{-8}

Temperature, K

Zinc Rhodium Ytterbium

Rhodium, Ytterbium (at %)
- —o— 8.69, 4.35, *P* = 0.00 GPa, Ref 191*
- —□— 8.69, 4.35, *P* = 2.00 GPa, Ref 191*
- —◇— 8.69, 4.35, *P* = 4.00 GPa, Ref 191*
- —×— 8.69, 4.35, *P* = 6.00 GPa, Ref 191*
- —+— 8.69, 4.35, *P* = 12.00 GPa, Ref 191*

Resistivity, ohm m × 10⁻⁸

Temperature, K

6.3 Resistance measurements as a function of temperature and pressure

Barium

99.5% Purity, Ref 89*

Resistivity normalised, $\rho (P)/\rho (0)$

Pressure, GPa

Dysprosium - 1

- ○ Heating Ref 141*
- □ Cooling Ref 141*

Resistance, ohm

Temperature, K

Gadolinium

Purity 99.50%

Temperature 295 K

⊖— Increasing Pressure, Ref 112*
⊟— Decreasing Pressure, Ref 112*

Resistivity, ohm m × 10⁻⁸

Pressure, GPa

Nickel - 1

Purity 99.997%
- P = 0.1 GPa, Ref 103*
- P = 2 GPa, Ref 103*

Resistance, ohms

Temperature, K

Nickel - 3

Purity 99.997%

—⊖—	*P* = 2.54 GPa, Ref 157*
—☐—	*P* = 3.04 GPa, Ref 157*
—◇—	*P* = 3.55 GPa, Ref 157*
—✕—	*P* = 4.05 GPa, Ref 157*
—+—	*P* = 4.55 GPa, Ref 157*

Resistance, ohms

Temperature, K

Oxygen Copper Barium Gadolinium Strontium

Copper, Barium, Gadolinium, Strontium (at %)
23.19, 7.73, 7.73, 7.73, Ref 107*

Oxygen Copper Barium Gadolinium Strontium Calcium

Copper, Barium, Gadolinium, Strontium, Calcium (at %)

— ○ — 23.14, 7.74, 7.74, 7.74, 0.08 Ref 108*
— □ — 22.92, 7.74, 7.74, 7.74, 0.31 Ref 108*
— ◇ — 22.75, 7.76, 7.76, 7.76, 0.54 Ref 108*
— ✕ — 22.52, 7.77, 7.77, 7.77, 0.58 Ref 108*

Normalised resistance, $R(T)/R$ (290 K)

Temperature, K

**Oxygen Copper Barium Gadolinium
Strontium Zinc**

Copper, Barium, Gadolinium, Strontium, Zinc (at %)

⊖ 23.11, 7.73, 7.73, 7.73, 0.077 Ref 107*
⊟ 22.99, 7.77, 7.77, 7.77, 0.31 Ref 107*
◇ 22.81, 7.78, 7.78, 7.78, 0.55 Ref 107*
✕ 22.96, 7.92, 7.92, 7.92, 0.79 Ref 107*

Normalised resistance, $R(T)/R$ (290 K)

Temperature, K

Oxygen Copper Barium Yttrium

Copper, Barium, Yttrium (at %)
25.00, 14.29, 7.14, Q = 1133 K, Ref 160*
26.67, 13.33, 6.67, Q = 1083 K, Ref 160*
25.00, 16.67, 8.33, Q = 1183 K, Ref 160*

Normalised resistivity, $R(T)/R$ (295)

Temperature, K

Oxygen (δ = 0) Copper Barium Yttrium Calcium Zinc

Copper, Barium, Yttrium, Calcium, Zinc (at %)

22.89, 15.52, 7.37, 0.39, 0.39 Ref 109*
22.64, 15.61, 7.03, 0.78, 0.78 Ref 109*
22.18, 15.56, 6.61, 1.17, 1.17 Ref 109*
22.00, 15.71, 6.28, 1.57, 1.57 Ref 109*

Oxygen Copper Barium Yttrium Cobalt Gallium

Copper, Barium, Yttrium, Cobalt, Gallium (at %)

22.33, 15.50, 7.75, 0.56, 0.37 Ref 135*

Normalised resistance, $R\,(T)/R\,(300)$

Temperature, K

Praseodymium

Purity 99.9%

—⊖— $P = 32$ GPa, Ref 90*
—▤— $P = 28$ GPa, Ref 90*
—◇— $P = 26$ GPa, Ref 90*
—✕— $P = 21$ GPa, Ref 90*

Normalized resistance, $R(T)/R$ (273 K)

Temperature, K

Selenium Niobium Vanadium

Niobium, Vanadium (at %)
- 24.95, 0.18 Ref 155*
- 24.92, 0.32 Ref 155*
- 24.92, 0.33 Ref 155*
- 24.91, 0.35 Ref 155*
- 24.81, 0.77 Ref 155*

Normalized resistance, $R(T)/R$ (300 K)

Temperature, K

Tellurium Bismuth Tin Iodine Antimony

Bismuth, Tin, Iodine, Antimony (at %)
39.94, 0.10, 0.03, 0.01 Ref 152*
39.93, 0.10, 0.06, 0.02 Ref 152*

Normalized resistance, $R\,(T)/R$ (293 K)

Temperature, K

Chapter 7
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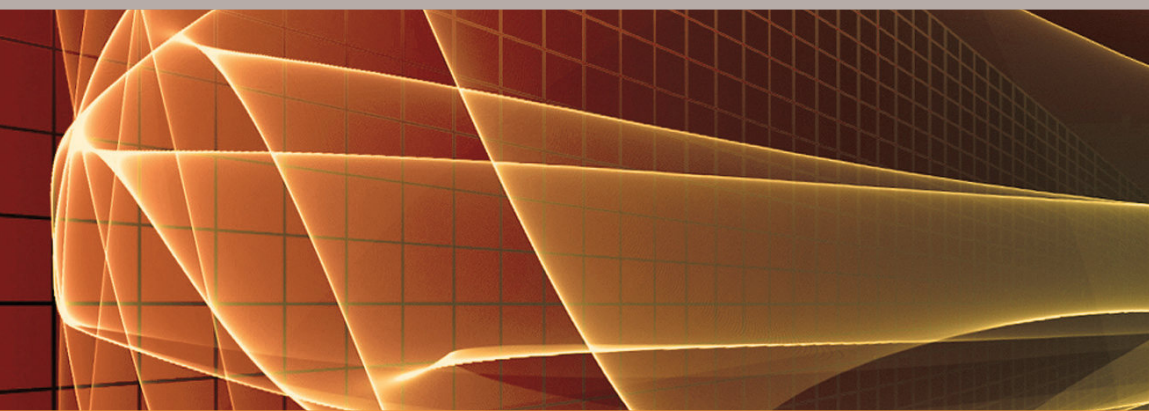
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Gordon Dyos is an experimental physicist whose work spans an enormous variety of subjects, from high-current spark gaps to the measurement of plasma wake concentrations in model atmospheric re-entry missiles, low speed laminar flow wind tunnels and megawatt pulsed arc light sources. He invented the concept and developed the halogen ceramic hob, transpiration cooling of plasma torch nozzles and steel sheet cutting processes using plasma torches. More recently, he has developed a 120kW glow discharge furnace for producing wrought metal from powdered feedstock. In retirement he has worked as a consultant to a plasma torch company and a defence department.

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