CONDUCTIVE MATERIALS, WIRES, AND CABLES

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Keywords: Conduction, conductivity, metals, metal alloys, materials, wires, cables, current, skin effect, insulation, barriers and shields, resources and sustainability.

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Summary

This chapter presents an overview of various conducting materials. This is followed by a discussion of materials used in the construction of wires and cables. Semiconductors, superconductors, cryogenic hyperconductors, resistive alloys, intermetallic compounds, metal matrix composites, solid electrolytes, fast ion conductors and ionomers are

beyond the scope of this article and will not be addressed.

1. Basic Concepts of Electrical Conduction

Electrical conduction occurs through transport of electric charge in response to an applied electric field. Electric charge is carried by electrons, electron holes, and ions. Electrical conductivity σ and its reciprocal, electrical resistivity, $\rho = 1/\sigma$, are physical properties of a material. While the range of values is somewhat arbitrary, electrical conductivity is very low in insulators, $\sigma < 10^{-15}$ S/cm ($\rho > 10^{21}$ Ωcm), intermediate in semiconductors, $\sigma = 10^{-5}$ to 10^{3} S/cm ($\rho = 10^{3}$ - 10^{11} Ωcm), very high in conductors, $\sigma = 10^{4}$ to 10^{6} S/cm ($\rho = 1$ - 10^{2}μΩcm), and infinite in superconductors.

Electrical conductivity, σ, is defined as the product of the number of charge carriers, n, the charge, e, and the mobility of the charge carriers, μ.

$$\sigma = n \cdot e \cdot \mu \tag{1}$$

For electronic conductors the electron charge, $e = 1.6 \times 10^{-19}$ coulombs, is constant and independent of temperature. The mobility, μ, usually decreases with increasing temperature due to collisions between the moving electrons and phonons, i.e., lattice vibrations. The number of charge carriers, n, remains constant for metallic conductors with increasing temperature, but increases exponentially for semiconductors and insulators. Thus at very high temperatures some insulators become semiconducting, while at low temperatures some semiconductors become insulators.

2. Electronic Band Model

Electronic conduction in a solid can be described in terms of the electronic band model. Quantum mechanics designates for each electron location probabilities as well as allowed energy levels also called electronic orbitals. Thus, an isolated atom represents a potential well with discrete electron energy levels. If two such atomic wells are brought into close proximity, then the isolated discrete energy levels split into a set of bonding and a set of antibonding levels. This is a consequence of the Pauli's exclusion principle, which forbids any two electrons to occupy the same energy level (neglecting electron spin). When a very large number, N, of such wells are brought into close proximity, then the original discrete energy levels overlap into quasi-continuous broad bands, each of which comprises N energy levels. The gaps between the bands may be preserved, but are smaller than between the original discrete levels; for some bands, notably the outer (or valence) bands, the gaps may even vanish and the bands overlap. The structure of the outer bands then determines whether a material is a conductor, semiconductor or insulator.

If a band is only partially filled, thermal excitation is sufficient to let the electrons easily move within the band continuum. On the other hand, if the band is completely filled no electron movement is possible. Since energy levels are progressively filled from the lowest to the highest, all the inner bands are completely filled and conduction occurs only in the outer or valence bands. In metallic conductors, the valence bands are only partially filled with electrons. The high number of mobile electrons, typically in the order of 10^{22}/cm^3, accounts for both the high electrical and thermal conduction in metals.

3. Conductive Materials

3.1. Conduction in Pure Metals

The charge transport in pure metals is caused by the drift of free electrons (or “electron gas”). (In some metals like beryllium and zinc, the movement of charge is considered to be due to electron holes.) Free electrons have comparatively high velocities and relatively long mean free paths until they collide with ions constituting the crystal lattice. This process is called scattering. In a perfect periodic lattice structure, no collisions would occur and the resistivity would be zero (not to be confused with superconductivity). Mean free paths of the electrons are limited by (a) ionic vibrations due to thermal energy, (b) the crystal defects, such as vacancies, dislocations, grain boundaries, Frenkel and Schottky defects, (c) the random substitution of impurity atoms for pure metal atoms on the pure metal lattice sites. As the temperature increases, the amplitudes of the ionic vibrations grow larger and scattering of the electrons increases. This offers more resistance to the flow of electrons. Resistivity increases roughly linearly with temperature at high temperatures. At low temperatures, where electron-electron scattering becomes the dominating scattering process, a T^5 dependence is predicted. Common pure metals have a resistivity of 1.5 to 150 μΩ-cm at room temperature. An overview of electric conductivities and temperature coefficients is given in Table 1.

Material	Thermal Conductivity [W/m-K]	Resistivity [μΩ-cm] at 20 °C	TCR [Ω/(Ω °C) in ppm]
Aluminum	226	2.65	4500
Antimony	23.8	40.1	5100
Arsenic	-	33.3	-
Barium	-	60 (0 °C)	6100
Beryllium	194	3.3	9000
Bismuth	9	117	4600
Cadmium	103	7.3	4300
Caesium	36.1	20	4800
Calcium	125	3.7	4600
Carbon (diamond)	1000-1300	$>10^{12}$	-
Carbon (pyrolytic graphite)	1950 (xy), 6 (z)	20 (xy), 40 (z)	-
Cerium	11.9	85.4	8700
Chromium	91.3	13.2	2400
Cobalt	96	6.24	6600
Copper	397	1.68	4300
Gold	317	2.214	3500
Hafnium	22.9	33.1	4400
Indium	80	8.8	5200
Iridium	145	5.3	3930

Iron	80.2	9.61	6510
Lead	35.3	20.8	3680
Lithium	76.1	9.35	5000
Magnesium	156	4.45	3700
Manganese	7.8	144	3700
Mercury	8.65	95.9	9700
Molybdenum	134	5.7	5300
Nickel	91	6.9	6920
Osmium	90	9.1	4200
Palladium	72	10.54	3770
Platinum	71.6	10.5	3927
Plutonium	8.4	141.4 (107 °C)	-2080 (107 °C)
Potassium	104	7.20	4600
Rhodium	150	4.51	4300
Rubidium	58	12.8	5300
Silver	429	1.587	4100
Sodium	128	4.69	5500
Strontium	-	23.1 (0 °C)	5000
Tantalum	57.55	13.5	3830
Thallium	45.5	16.6	5200
Thorium	49.2	14	3800
Tin	66.6	11 (0 °C)	3640
Titanium	21.9	42	3500
Tungsten	174	5.3	4500
Uranium	28	27	2100 (27°C)
Vanadium	31.6	19.7	3900
Zinc	119.5	5.92	4190
Zirconium	22.6	42.1	4000

Table 1: Electrical properties of some pure metals

3.2. Common Elemental Conductors

Copper smelting operations have been traced back to at least 7000 years before present. Today, electrical and electronic uses dominate the copper markets. The advantages of copper are its high thermal and electrical conductivity, which is only surpassed by pure silver. The grade and quality of copper is very important with regard to its intended application. For instance, conductivity is greatly influenced by impurities and mechanical working. The International Annealed Copper Standard (IACS) assigns a 100% to copper with the resistivity of 1.724 μΩ-cm at 20 °C. For electrical applications high conductivity copper is used which easily exceeds these 100%.

Copper is easily soldered to and has good mechanical characteristics including tensile strength, toughness and ductility. Due to its low coefficient of thermal expansion and high tensile strength, copper finds widespread use in overhead transmission lines. Copper is fairly corrosion resistant and tarnishes only superficially in air. When copper is used for contacts, oxidation is not desirable. In order to prevent oxidation, copper can be plated with silver or nickel. Nickel-coated copper conductors can be used at temperatures up to 300 °C. There is not enhanced ‘bimetallic’ corrosion at defective areas of the coating as sometimes seen with silver. Nickel plating is also often used as a barrier coating under the final gold plating on electronic conductors.

Aluminum is the second most abundant metal after silicon and is second only to iron measured in quantity or value of production. At 20 °C commercial, hard-drawn aluminum has a conductivity of 61 % that of copper while being a third as dense. This makes it useful for the production of lightweight shielding cans, component mounts/chassis, power line conductors, heat sinks, mechanical fixtures, etc. Aluminum is also a basic integrated circuit metallization element. Its excellent resistance to corrosion in many environments is due to the protective, highly adherent native oxide film. Aluminum can be ‘anodized’ to give an artificial oxide film for increased corrosion protection.

Historically, silver has been used for jewelry and as a basis for monetary systems. Primary source of silver is its recovery as a byproduct of copper, gold, lead, or zinc production. Today the most important use for silver is in the manufacture of photographic materials. Silver is also an excellent conductor. Since it is a very soft metal, it is not normally used in its pure state, but is alloyed with a hardener, usually copper. Silver is malleable and ductile and does not oxidize in air at room temperature. Silver does, however, absorb considerable amounts of oxygen at elevated temperature and is tarnished by sulfur compounds. Its major electric applications are as contacts on relays for currents less than 20 A, and in instruments rated for small currents. In presence of humidity and electric fields silver will migrate to form fine silver threads or dendrites between conductors eventually causing electric shorts. If used in microelectronic circuits, silver migration needs to be contained by diffusion barriers such as tungsten, palladium or nickel.

Pure gold has unsurpassed resistance to oxidation and sulfidation. However, its softness and susceptibility to erosion limits its use in electrical contacts to currents below 0.5A. Gold sometimes forms a carbonaceous deposit in presence of volatile organic compounds increasing contact resistance. The low hardness of gold can be increased by alloying with copper, silver, palladium, or platinum. Gold is used for fine wire connections and as a contact surface in integrated and hybrid circuits.

The refractive platinum metals (Pt, Pd, Rh, Ir, Os, Ru) are highly resistive to corrosive environments. Stable thermoelectric behavior, high resistance to spark erosion, tarnish resistance, and broad ranges of values of electrical resistivity and temperature coefficient of electrical resistance make platinum metals useful for a number of electrical applications such as thermocouples or contacts for telephone relays. Platinum and palladium are most commonly used for these applications. Low values of electrical and thermal conductivity and high cost generally exclude them, however, from use for currents above 5 A.

Tungsten is stronger than any common metal at temperatures over 2000 °C and has the highest melting point of all metals, 3380 °C. The electrical resistivity is about three times as high as that of copper, but better than that of platinum or nickel. The high temperature stability of tungsten is exploited in lamp filaments and electronic filaments in which it serves as a light- or electron-emitting cathode material. Tungsten is used as a wear-resistant material for contacts.

Molybdenum is not as widely used as tungsten as it oxidizes more readily and erodes faster on arcing. Molybdenum contacts are advantageous where mass is important. It is widely used for mercury switches because it can be wet, but is not attacked by mercury.

Graphite is a crystalline, allotropic form of carbon of very high melting point (3700 °C). The electrical conductivity of graphite is slightly less than that of metals and their alloys. Pure carbon, in contrast, is a semiconductor with a negative coefficient of resistance.

In electrical engineering, carbon (graphite) elements are extensively used as: a) brushes for electrical machines; b) carbon electrodes for electric-arc furnaces, electrolytic baths and welding; c) non-wire resistors; d) battery cell elements; and e) for microphone powders and other components of telecommunication equipment.

Carbon and graphite are used also as sliding electrical contacts because of their ability to withstand temperatures up to 3000 °C, low density, ability not to weld to metals, self lubrication properties and inexpensive production. Graphite fibers have a very high thermal conductivity, far greater than that of copper, and are being used for lightweight, heat-management applications.

3.3. Conductivity of Dilute and Concentrated Metal Alloys

For a dilute alloy, the solute impurity atoms, which constitute typically less than 5%, dissolve randomly and by substitution into the solvent lattice giving rise to additional impurity scattering. The resistivity of an alloy would then be expected to be larger than that of its pure metal solvent at the same temperature. The Bloch model suggests that the electrical resistivity is mainly a consequence of disturbances in the atomic periodicity in the crystal structure.

For more concentrated alloys, complete solubility between the constituent atoms rarely occurs and most binary alloy systems are characterized by the presence of miscibility gaps and intermetallic compounds at room temperature. The alloy is thus a mixture of two disordered solid solutions. Depending on the equilibrium phase diagram, the temperature, and the composition, an alloy may exist as a mixture of many phases, each with its own distinct resistivity.

Qualitatively, completely miscible binary solid solutions show a bell shaped resistance curve, whereas completely immiscible binary composites show a depressed line between the levels of resistivity of the pure elements. Resistivity changes with composition in multiphase systems can be very complicated, especially when they involve intermetallic compounds, partial solubility, and multiple solubility gaps. Intermetallic compounds possess a higher degree of order than the surrounding solid solutions often leading to local resistivity minima.

3.4. Conductive Alloys

Copper alloys containing metals such as tin, cadmium, beryllium, chromium and zirconium are called bronzes. They have a lower electrical conductivity (20 to 85%) than pure copper, but are more resistant to corrosion and wear. Their greater tensile strength compared to copper allows some of these alloys to be used as trolley wires and in high strength fine wire applications.

Steel, which is iron with ~1 wt. % of C, is not very often used as a conducting material because of its low electrical conductivity (stainless steel 304 has a resistivity of 72 µΩ-cm). This is despite its good mechanical properties and low cost. Steel is also easily corroded by moisture and heat. For corrosion prevention it can be galvanized by dipping it into molten zinc. Galvanized or copper-covered steel is used for high-voltage transmission spans where tensile strength is more important than high conductance. Steel is also used for third rails in electrically powered trains.

Material	Thermal Conductivity [W/m-K]	Resistivity [µΩ-cm] at 20 °C	Liquidus/Solidus °C
48Sn52In	34	14.7	118
42Sn58Bi	19	39	138
62Sn36Pb2Ag	49	14.8	179
63Sn37Pb	51	15	183
96.5Sn3.5Ag	33	10.8	221

Table 2: Properties of some eutectic solder alloys

Soldering and brazing are simple joining processes in which metals are wetted and joined together by a dissimilar metal of a lower melting temperature. Most conventional solders are used below a temperature of 300 °C. Solders are typically alloys of tin with other metals such as lead, silver, copper, antimony, cadmium, indium, and bismuth. They are generally good conductors and are used to metallurgically join metal conductors. The driving force for joining is the formation of intermetallic tin compounds with metals such as Cu, Ni, Au, Pd and Ag. Lead-tin solders are most commonly used for electronic applications. The eutectic composition (63Sn37Pb) has good mechanical properties combined with excellent wettability. Properties of some very common eutectic solders are given in Table 2. Antimony is occasionally added to increase the strength of lead-tin alloys. To minimize scavenging of silver, small amounts of silver may be added to saturate the solders. Intermetallic gold compounds in solder dissolved during soldering operations may impart brittleness to the joints. If not controlled properly, aluminum, cadmium, and zinc impurities are also detrimental to lead–tin solder properties.

Above a temperature of 400 °C, brazes or hard solders are used to join two or more pieces of metals. Brazes refer to copper-zinc, copper-silver, copper-aluminum, aluminum-zinc, and aluminum-silicon alloys. Similar to solders, joint formation is often driven by an intermetallic reaction of a braze component with the metals to be joined. One such example is brazing solder, which has 51% copper and 49% zinc content. Another example, "Phos-copper", a phosphor copper, flows at 750 °C. It retains 98% of the conductivity of copper.

3.5. Special Electric and Electronic Applications for Metals and Alloys

3.5.1. Metals and Alloys for Electrical Contacts

Electrical contacts are temporary junctions between two conductors. Materials for this application require a low contact electrical resistance, resistance to high contact force and mechanical wear, high voltage breakdown strength, and need to withstand arcing. Due to corrosion, contact surfaces usually acquire a film of oxides which has low conductivity and reduces the effectiveness of electrical contacts. Acceptable contact materials include copper, molybdenum, nickel palladium, platinum silver, and tungsten. For high voltage (100,000 V) and high amperage (10,000 amp) applications, alloys of precious and refractory metals are used. Typical alloys are Ag(40-50)Mo(50-60), Ag(40-75)W(25-60), and Cu(55-70)W(30-45). Sliding contacts in variable resistors and rheostats are made of bronze-nickel or platinum alloys.

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Biographical Sketches

Lutz Brandt received his Ph.D. degree in Metalorganic Chemistry (1991) from the University of Würzburg, Germany. Activities since then include fabric softener development at Procter & Gamble in Belgium, postdoctoral research at UCLA (CA) in MOCVD and soluble, noble metal nano-clusters, R&D at Ormet Corp. (CA) in composite conductive materials for jumper wires, via fill, and EMI shielding applications. Since 2001 he is a Technical Manager for Classical PTH plating processes at the Atotech company in Berlin, Germany.

Goran Matijasevic holds a Ph.D. in Physics from the University of Irvine, California. As a Research Director, he coordinated research activities into applications of conductive composites at Ormet Corporation, CA. He recently (2002) joined UC Irvine and the Integrated Nanosystems Research Facility as Research Coordinator developing collaborative and interdisciplinary projects, in the areas such as nano and micro technology for communications and biomedical applications.