CONDUCTING MATERIALS

This article will present briefly principles of electrical conduction followed by a discussion of electron- and ion-conducting materials. Apart from well-known metals and alloys for electrical wires, cables, and contacts, several new classes of synthetic organic, inorganic, and composite conductors (1,2) have become available. The particular attraction of these materials is that one can tailor their electronic properties for microelectronic, optoelectronic, photovoltaic, thermoelectric, and superconducting uses.

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 the material. While the range of values are somewhat arbitrary, electrical conductivity is very low in insulators, $\sigma < 10^{-15}$ S/cm ($\rho > 10^{21}\ \mu\Omega \cdot \text{cm}$), intermediate in semiconductors, $\sigma = 10^{-5}$ S/m to 10^{3} S/cm ($\rho = 10^{3}$ to $10^{11}\ \mu\Omega \cdot \text{cm}$), very high in conductors, $\sigma = 10^{4}$ S/m to 10^{6} S/cm ($\rho = 1$ to $10^{2}\ \mu\Omega \cdot \text{cm}$), 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, $e = 1.6 \times 10^{-19}$ C, 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.

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 forms a potential well with discrete electron energy levels. If two such atomic wells are brought into 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 sets (bonding and antibonding levels). When a large number, N, of such wells are brought into proximity, then the original discrete energy levels broaden into quasi-continuous 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) band, the gaps may even vanish and the bands overlap. Whether a certain material is a conductor, semiconductor, or insulator may then be described by the electronic band theory.

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 on the order of $10^{22}/\text{cm}^3$, ac-

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counts for both the high electrical and thermal conduction in metals.

In network solids such as diamond or silicon, valence bands are completely filled consistent with strong directional covalent bonds. In addition, there is an appreciable energy gap to the next empty (conduction) band. Electrons cannot move freely within the bands, and these materials do not efficiently conduct electricity. In diamond, for instance, the energy gap between the valence band and the conduction band is 6 eV (1 eV = 1.6×10^{-19} J), making it an excellent insulator. In semiconductors, such as silicon, the band gap between the valence band and the empty conduction band is smaller; typically in the range of 0.5 eV to 3.0 eV. At room temperature, the thermal energy, $k_BT = \sim 0.03$ eV, is small compared to the energy gap. With increasing temperature, more and more electrons have sufficient thermal energy to be promoted into the empty conduction band. The vacated positions in the valence band are regarded as positive holes, which contribute to the electrical current by moving in the opposite direction of the negatively charged electrons. Pure silicon, for example, has about 10^{10} electron and hole carriers per cm^3 at ambient temperature.

Exertion of pressure onto solids narrows the valence and conductance band gaps and ultimately, with high enough pressure, all materials should show a metallic transition. The diatomic I_2 molecules become metallic at ~210 kbar, and even the noble gas xenon turns into a metallic phase at 1.3 Mbar. In metals themselves, pressure tends to decrease the amplitudes of lattice vibrations and therefore causes a slight decrease in resistivity. Pressure effects on synthetic conductors are more varied and not well investigated. In some cases and at very low temperatures, exertion of high pressure allows one to achieve superconductive properties.

Thermal Conductivity

Thermal conductivity in solids is provided by lattice vibrations (phonons) as well as the movement of free electrons. In general, metals that have free electrons are better heat conductors than nonmetals, and crystalline materials, which have ordered lattices, conduct more readily than amorphous materials. The thermal conductivities of pure metals decrease with increasing temperature as electrons are impeded in their flow, whereas the conductivities of nonmetals increase; alloys, depending on composition, may show either behavior. For pure metals, where electrons are the major heat carriers, the thermal conductivity k_{th} and the electrical conductivity k_{el} are related by the relationship $k_{th}/k_{el} = LT$, with the Lorentz number L having a value from 22 $\mathrm{V}^2/\mathrm{K}^2$ to 29×10^{-9} $\mathrm{V}^2/\mathrm{K}^2$.

Superconductivity

Superconductors carry electrical current without any energy loss due to resistance. The phenomenon of superconductivity came to be known in 1911 by observing a thin column of mercury abruptly losing its resistance when immersed into a liquid helium bath at 4.2 K. It was later established that superconductivity can exist only below a critical temperature T_c and a critical magnetic flux density B_c. A superconductor, unlike a perfect conductor, does not conserve the magnetic field flux within it, but rather expels the flux (Meissner effect). Pellets of superconducting yttrium barium copper oxide ceramic hover above magnets at liquid nitrogen temperature. The effect has prompted the proposal of levitating vehicles on rails and frictionless ball bearings.

The quantum theory of superconductivity describes a low-temperature condensed state of electrons in which they interact, through the atomic lattice, to form temporary pairs (Cooper pairs). An electron traveling through the crystal exerts an attractive force on the ions, pulling them together as it passes between them. While the metal ions remain close together, they create a region of abnormally concentrated positive charge to which a second electron can be attracted. Distance between the electrons is very large, about 10,000 times the distance between neighboring ions. The interaction between the electrons is therefore very weak and can be disrupted by thermal vibrations of the ions. This explains why the effect only occurs at low temperatures. Cooper pairs, unlike the electrons (which are fermions), are bosons, which can occupy all the same low-energy state. Because of their low-energy state, Cooper pairs are not readily scattered and flow unimpeded. Unfortunately, this theory does not allow the prediction of the new high-temperature superconductor materials.

CONDUCTIVE MATERIALS

Metals and Alloys

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 (1) ionic vibrations due to thermal energy; (2) the crystal defects, such as vacancies, dislocations, grain boundaries, Frenkel and Schottky defects; and (3) 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 $\mu\Omega \cdot \mathrm{cm}$ to 150 $\mu\Omega \cdot \mathrm{cm}$ at room temperature. An overview of electric properties is given in Table 1.

Most Commonly Used Metal Conductors. Aluminum, a basic integrated circuit metalization element today, is also used for the production of lightweight shielding cans, component mounts/chassis, power line conductors, heat sinks, mechanical fixtures, etc. Its excellent resistance to corrosion in many environments is due to the protective, highly adherent oxide film that develops in the presence of oxygen.

Copper is the most widely used electrically conducting material. Its advantages are high thermal and electrical conductivity (surpassed only by pure silver) and relatively low cost. 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 ten-

Table 1. Electrical Properties of Some Pure Metals

Material	Thermal Conductivity (W/m · K)	Resistivity ($\mu\Omega \cdot$ cm) at 20°C	TCR ($\Omega/\Omega \cdot$°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

sile strength, copper finds widespread use in overhead transmission lines. Copper is fairly corrosion resistant and tarnishes only superficially in air.

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 than that of metals and their alloys. Pure carbon, in contrast, is a semiconductor with a negative temperature coefficient of resistance. In electrical engineering, carbon (graphite) elements are extensively used as (1) brushes for electrical machines; (2) electrodes for electric-arc furnaces, electrolytic baths, and welding; (3) nonwire resistors; (4) battery cell elements; and (5) microphone 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-lubricating 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.

Silver is a very soft metal and not normally used industrially 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 industrial applications are as electric contacts on relays and in instruments rated for small currents. Silver migrates under electric potential and, if used in microelectronics circuits, needs to be contained by diffusion barriers such as tungsten, palladium, or nickel.

Pure gold has unsurpassed resistance to oxidation and sulfidation. However, susceptibility to erosion limits its use in electrical contacts to currents below 0.5 A. Gold sometimes forms a carbonaceous deposit in the presence of volatile organic compounds, increasing contact resistance. The low hardness of gold can be increased by alloying with copper, silver, palladium, or platinum.

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 electrical resistivities and temperature coefficients 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. Low electrical and thermal conductivities 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 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 in electrical engineering as a wear-resistant material for contacts and parts of vacuum devices. 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 is wetted, but not attacked by mercury.

Metal Alloys

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

$$\rho_a(T) = \rho_p(T) + \rho(c)$$

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.

Table 2. Properties of Some Eutectic Solder Alloys

Material	Thermal Conductivity (W/m · K)	Resistivity ($\mu\Omega \cdot$ cm) at 20°C	Liquidus/Solidus (°C)
48Sn52In	34	14.7	118
42Sn58Bi	—	39	138
62Sn36Pb2Ag	49	14.8	179
63Sn37Pb	51	15	183
96.5Sn3.5Ag	33	10.8	221

Table 3. Properties of Some Resistance Alloys

Material	Composition	Resistivity ($\mu\Omega \cdot$ cm) at 20°C	TCR ($\Omega/\Omega \cdot$ °C in ppm)	Thermoelectric Potential (μV/C)
Manganins	Cu13Mn	48	15	1
	Cu13Mn4Ni	48	15	−1
	Cu10Mn4Ni	38	10	−1.5
Constantans	Cu43Ni	49	20	−43
	Cu45Ni	50	40	−42
NiCrAl alloys	Ni20Cr3Al2Cu (Fe, Mn)	133.0	20	−0.1
	Ni20Cr3Al5Mn	135.5	20	−0.1

Conductivity of Concentrated Alloys. For concentrated alloys, complete solubility between the constituent atoms rarely occurs, and most binary alloy systems are characterized by the presence of miscibility gaps at room temperature. The alloy is then a mixture of two disordered solid solutions. Depending on the equilibirum phase diagram, the temperature, and the composition, an alloy may exist as a mixture of many phases, each with its own distinct resistivity (3–5).

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

Conductive Alloys. Steel, which is iron with ~1 wt% C, is not often used as a conducting material because of its low electrical conductivity (stainless steel 304 has an electrical resistivity of 72 $\mu\Omega \cdot$ 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.

Copper alloys containing tin, cadmium, beryllium, and certain other metals are called bronzes. They have a lower electrical conductivity (20% to 85%) than pure copper but are more resistant to corrosion and wear. The greater tensile strength allows some of these alloys to be used as trolley wires.

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 (6) 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. Properties of some very common eutectic solders, such as 63Sn37Pb, are given in Table 2. The driving force for joining is the formation of intermetallic tin compounds with metals such Cu, Ni, Au, Pd, and Ag.

Brazes or hard solders are used to join two or more pieces of metals above a temperature of 400°C. 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 and retains 98% of the conductivity of copper.

Resistive Alloys. Resistive alloys are usually solid solutions of metals with a disordered structure. The disordered structure leads to electron scattering and therefore to high resistivity and comparatively low values of temperature coefficient of resistance (TCR). Pure metals, in contrast, typically have very high TCRs of several thousand ppm. Additional requirements for resistive alloys are high mechanical strength, high melting point, corrosion resistance at high temperatures, and constant resistivity over time.

Resistive alloys used for precision resistor applications should ideally have a TCR equal to zero over the operating temperature range. Another requirement is a small or negligible thermoelectric potential versus the connecting conductor material, ensuring absence of thermoelectric effects such as parasitic currents and voltages due to temperature gradients. Manganins, which are solid solutions of copper, manganese, and nickel, are used in precision instruments, resistance standards, bridge potentiometers, and resistance boxes. They exhibit almost temperature-independent ohmic resistance while their thermoelectric potential under bimetallic contact with copper is low (~1 μV/C). Constantans, a class of copper-nickel alloys, are used in rheostats and similar control devices. Constantans have a relatively high thermoelectric potential versus copper (~40 μV/C) (Table 3).

Ni–Cr, Ni–Cr–Fe, and Fe–Cr–Al alloys are known as heat-resistant, conducting materials that are used for heating elements in heaters and furnaces (Table 4). The heat resis-

Table 4. Properties of Some Resistance Heating Alloys

Material	Composition	Resistivity ($\mu\Omega \cdot$ cm) at 20°C	Maximum Work Temperature (°C)
NiCr alloys	Ni20Cr1.5Si	108	1150
	Ni30Cr1.5Si	118	1200
NiCrFe alloys	Ni20Cr43.5Fe1.5Si	101.5	925
	Ni30Cr33.5Fe1.5Si	105.5	—
FeCrAl alloys	79.5Fe15Cr5.2Al	137.0	1260
	72.5Fe22Cr5.5Al	145.5	1375
Silicon carbide	SiC	99.5–199.5	1600
Molybdenum disilicide	$MoSi_2$	37	1700–1900
Graphite	C	910	400 (air), 2205 (inert)

tance of these alloys is due to the formation of a dense, nonvolatile, strongly adherent surface oxide film (e.g., NiO, Fe_2O_3, Cr_2O_3) that excludes access of further air/oxygen to the alloy. However, sulfur is destructive to Ni–Cr and Ni–Cr–Fe alloys, usually more so with higher nickel content.

Intermetallic Compounds. Intermetallic compounds (IMCs) are compounds of two or more metals that have a distinct structure in which the metallic constituents are usually ordered on two or more sublattices, each with its own distinct population. Deviations from the precise stoichiometry are, however, common and can be exploited to tailor lattice constants. Due to their highly ordered structure, intermetallic compounds have a high melting point and are very hard (brittle).

The intermetallic compound Au–Hg has been used for gold recovery and gilding of less noble metals for more than 3000 years. SiC and $MoSi_2$ are well-known resistance heating materials (Table 4). Today, apart from many structural and high-temperature applications, intermetallic compounds have found various advanced electrical uses (7,8). Intermetallic superconductors, such as Nb_3Sn, Nb_3Al, or YPd_2B_2C (9), are investigated for high-magnetic-field generators, high-speed analog devices, and power conservation. Compound semiconductor materials such as GaAs and InP exhibit very high electron mobilities, leading to applications in very high-speed transistors. IMCs such as HgCdTe, $CuInSe_2$, $CuGaSe_2$, and $CuGaSe_2$ are useful for optoelectronic applications such as optical switches, solar cells, photodetectors, light-emitting diodes, and lasers. Intermetallic compounds such as PbTe, Bi_2Te_3, and transition metal silicides, such as the nonstoichiometric $MnSi_{1.72}$, show a high thermoelectic effect (TE) and are used in TE thermocouples, TE generators, TE radiation detectors, and TE coolers.

Intermetallic compounds have proven very effective as diffusion barriers for thin film semiconductor devices. Diffusion of one species into another causes rapid degradation of electrical contacts. Intermetallic diffusion barriers are also used to prevent degradation of fibers in metal matrix composite fabrication, to improve wettability in soldered or brazed joints, and to prevent interdiffusion of the components of a brazing alloy with the substrate material. Diffusion barrier materials are chosen to limit reaction with either the substrate or the overlayer. Intermetallic compound examples for diffusion barriers include Al_3Ti, Al_3Hf, Co_2Si, and NiSi. In IC fabrication, silicides such as WSi_2, $MoSi_2$, and $TaSi_2$, which can be easily etched, are used for gate metallization. TiN is an effective barrier between Al and the Si substrate.

Special Electric and Electronic Applications for Metals and Alloys

Metals and Alloys for Fuses. Fusible metals and alloys are used for circuit interruption when current density rises beyond the rated values. At the fusing current, the fuse material melts from joulean heating, causing an open circuit and preventing possible damage of the circuit. Typical low-melting-point fuse materials are Pb (327°C), Cd (321°C), Bi (271°C), Sn (232°C), In (156°C), Bi80Sn (200°C), Bi50Pb (160°C), Pb50Sn18Cd (145°C), Bi26Pb20Cd (103°C), and Bi25Pb13Sn10Cd (72°C). The fusing current is given by the relation $I_{\text{fuse}} = AD^n$, where A and n are empirical constants for a given metal and D is the wire diameter.

Metals and Alloys for Thermocouples. Thermocouples are invaluable for temperature measurements. A thermocouple consists of wires of two dissimilar materials, a positive and a negative component, which are joined at their ends to form a closed loop. If the two junctions are kept at differential temperatures, an electrical current flows (Seebeck effect). Conversely, if a current flows through those junctions, a reversible change in heat content (i.e., heating and cooling) can be perceived (Peltier effect). For thermocouples, typical positive components are Fe, Ni–Cr, and Cu, with constantan as the negative component. Materials with large Seebeck and Peltier effects may be used for thermoelectric cooling. Thermoelectric couples based on Be–Te–Se couples give cooling of at least −50°C and are used in small, silent refrigerant devices.

Metals and Alloys for Electrical Contacts. Electrical contacts are temporary junctions between two conductors. Materials for these applications require a low-contact electrical resistance, resistance to high-contact force and mechanical wear, high-voltage breakdown strength, and the ability 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 A) 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.

Metals and Alloys for Thin Film Applications. Thin film conductive and resistive materials (10) are used for the fabrication of microelectronic devices. Materials are deposited by physical (PVD) or chemical (CVD) vapor deposition methods. Typical conductor materials are gold, aluminum, silver, and copper. NiCr and TaN are the most common resistor materials. Diffusion barriers are needed to prevent the degradation of metal/metal interfaces. Nickel is an effective barrier material for Au/NiCr interfaces, preventing Cr from diffusing into Au. Palladium, platinum, molybdenum, and tungsten serve as barrier materials and as adhesion layers.

Metal oxide films from tin (usually tin–antimony alloys), indium (usually indium–tin alloys), tin-cadmium alloys, and zinc have been reported to exhibit high electrical conductivity combined with the great optical transparency. The oxides are very robust and environmentally stable. Indium tin oxide (ITO), which reaches resistivities down to $4 \times 10^2\ \mu\Omega \cdot \text{cm}$, is employed to form transparent electrical contacts for liquid crystal displays.

Metals from Metal-Organic Compounds. Increasingly, metal-organic (or organometallic) compounds are employed to fabricate pure metal conductors and films. These compounds are thermolabile and lose their organic constituent upon heating. Precious metal conductors can be obtained often by processing in air, while base metals have to be handled under inert or reducing atmospheres to avoid formation of metal oxides. Metal–organic compounds can be applied in form of inks, sprayed on as organic solvent solutions, or deposited by metal-organic chemical vapor deposition (MOCVD) (11,12) methods, a complement to the thin film CVD methods.

Metals for Cryogenic Hyperconductors. Cryogenic hyperconductors are metals whose resistivity is rather low (but still higher than superconductors) at the cryogenic temperatures

Table 5. Superconducting Metals and Alloys

Type I	T_c (K)	Type II	T_c (K)	Type III	T_c (K)
Al	1.18	Pb–In	7.0	$La_{1.85}Sr_{0.5}CuO_4$	40
In	3.41	Pb–Bi	8.3	$YBa_2Cu_3O_7$	95
Sn	3.72	Nb–Ti	9.5	$Bi_2Sr_2CaCu_2O_8$	85
Pb	7.20	Nb–N	16.0	$Bi_2Sr_2Ca_2Cu_3O_{10}$	110
Nb	9.25	$PbMo_6S_8$	15.0	$Tl_2Ba_2CaCu_2O_8$	108
		V_3Ga	15.0	$Tl_2Ba_2Ca_2Cu_3O_{10}$	125
		V_3Si	16.0		
		Nb_3Sn	18.0		
		Nb_3Ge	23.0		

of liquid helium (4.2 K), neon (27.1 K), or nitrogen (77.4 K). At these temperatures the electrical resistance of the hyperconductors drops sharply. This is explained by the cessation of ionic vibration in the crystal lattice, allowing the electrons to pass without scattering. The ohmic loss is minimized. The degree of scattering is then essentially determined by the impurities disturbing the crystal lattice. Typical hyperconductors are copper (99.999%), aluminum (99.99%), and beryllium (99.95%). Hyperconductive wires of electrical machines and transformers allow operation at cryogenic temperatures without much loss. This reduces their overall dimensions and mass.

Superconducting Metals and Alloys. Although superconductivity has been observed for a number of metals and inorganic and organic compounds, many good conductors, such as Cu, Au, Ag, and Pt, have not yet been transferred into a superconducting state. Superconductors are commonly classified according to the influence of the magnetic field on superconducting properties. Type I superconductors lose their superconductivity at weak magnetic fields. Types II and III have a higher critical magnetic field (Table 5).

Applications of current superconductive materials are limited by the low critical temperatures, the internal, current-generated magnetic field, as well as processibility issues due to brittleness. Nb is envisaged for use in alternating current equipment such as power cables. Nb_3Zr, Nb_3Sn, and $V_{2.95}Ga$ have shown some feasibility for cryogenic magnets. Other futuristic applications are cryotron computers, where the binary state is either superconductive or nonsuperconductive, noncontact switches, and superconducting memory devices. Materials such NbN, BSCCO, and $YBa_2Cu_3O_{7-x}$ films have been studied for their use in electronic transmission lines. High-T_c YBCO films on MgO substrates have been considered as active antennas for microwave detection.

Nanometals and Semiconductors. Nanosized metal (Au, Ag, Pd, Pt) and semiconductor (CdSe, InP) clusters smaller than 10 nm and containing a few hundred to a few thousand of atoms exhibit size-dependent electronic properties that drastically differ from the bulk. While initial interest was mainly spurred by catalytic and magnetic recording applications of nanosized transition metal clusters, it became clear that small metal and semiconductor particles may also serve as functional units in innovative nanoelectronic devices for high-capacity computers and optoelectronic switches (13). This requires the assembly of clusters into stable, interconnected, low-dimensional structures, such as quantum wells (2-D), quantum wires (1-D), and quantum dots (0-D), and has been achieved so far with various degrees of success. Nanoclusters are easily prepared by vapor condensation methods, thermolysis of metalorganic compounds, or reduction of metal salts in solution. Nanosized gold clusters, which have a deep purple color, have long been used as coloring agents for cell organelles.

Synthetic Conductors

Intrinsically Conducting Polymers. Polymers find widespread use as structural and functional materials. Among several advantages, they are lightweight and high strength and can be customized. In the electronic industry, polymers have primarily been used in substrate materials as well as insulation layers separating conducting materials. In contrast, it has been difficult to develop intrinsically (or inherently) conducting polymers (ICPs) with a useful mix of electrical and mechanical properties. The development of intrinsically conducting polymers (14) is spurred by the hope of replacing the inorganic conductors used in electronic devices. While conductive polyaniline was developed more than a century ago, it was a doped polyacetylene that launched the recent interest in electrically conducting organic polymers (15). About a dozen ICP classes with relatively high conductivities have been developed (Table 6).

Conductive polymers have a backbone like a chain of atoms or a stack of molecular poker chips. They are approximate one-dimensional conductors, materials that conduct in one dimension only. A common feature of an undoped (pristine) conducting polymer is the extended π-conjugated system, which is formed by the overlap of carbon p_z orbitals and alternating carbon-carbon bond lengths along the polymer chain. Polyacetylene $[(CH)_x]$, polyaniline (PAN), polypyrrole (PPy), polythiophene (PT), and polyphenylene vinylene (PPV) represent some of the most common of the conducting polymer families. These polymers become conductive upon exposure to acids or adequate oxidation or reduction, called "doping" here. This doping is carried out by chemical or electrochemical means. It changes the polymers from insulating to conducting, increasing the conductivity by up to 10 orders of magnitude or more. Both *n*-type (electron donating) and *p*-type (electron accepting) dopants have been used in creating conductive polymers. Dopant atoms find themselves interstitially between chains and contribute charge to the polymer backbone. A considerable amount of work is being done to determine the nature of the insulator-metal transition. Great uncertainties still exist regarding the structures of the doped and undoped phases, degree of polymerization, inhomogeneity of doping, and structural changes occurring in the doping process. Conduction concepts involve soliton, polaron, and

Table 6. Resistivity of Some Polymers

Material	Resistivity ($\mu\Omega \cdot$ cm)
Copper	1.67
Polyacetylene	$10–10^3$
Polyphenylene vinylene, polythiophene, polypyrrole, polyaniline (emeraldine)	$10^3–10^4$
Ionically conductive polymers	$10^7–10^{14}$
Polystyrene, fluoropolymers	10^{24}

bipolaron electronic states, which "hop" along the chain. "Interhopping" between adjacent chains is also believed to occur.

The initial work on polyacetylene doped with iodine produced a resistivity of $10^4\ \mu\Omega \cdot \text{cm}$ (10^2 S/cm). Further research yielded materials with room temperature resistivity of 10 $\mu\Omega \cdot \text{cm}$, while other conducting systems have also produced materials with resistivities of $10^3\ \mu\Omega \cdot \text{cm}$. There is a problem with most of these polymers in that the conductivity decreases with temperature, although higher-conductivity polymers show less temperature dependence.

Scientists have been working on developing polymers with reduced band gaps. Conjugated organic polymers conduct electricity only when doped with an oxidizing or reducing agent. The band gap in most of the undoped polymers is between 1.5 eV and 4.0 eV. They are thus more like semiconductors. Work on polycroconaines and polysquaraines has yielded band gaps as small as 0.5 eV.

Since the introduction of commercial-grade conductive polymers in the mid-1980s, ICPs have found use in a number of applications, including button battery cells (polyanilines, emeraldine base), in polymer-coated fabric for static-control applications (polypyrrole), as membranes for static dissipation, and as electromagnetic interference shielding materials (polythiophenes). The transparency of the conducting polymers can be of use in some of these applications. A number of other applications are rapidly being developed, including in light-emitting diodes (LEDs), for sensors, for corrosion protection, and for joining of plastic materials. Possible applications for conductive plastics include automobile ignition cables (low currents), telephone receiver cables (flexibility required), solar photovoltaics cells (for inexpensive coverage of large surfaces), and semiconductors. The ability to disperse very small amounts (as low as 1 wt %) of conducting polymers in insulating polymers to form an interpenetrating network-type structure (16) will further increase the number of potential applications.

The potential of the intrinsically conductive polymers is tempered by the realization that most of these materials are unstable in the presence of air and moisture, thus limiting their application. Furthermore, application of the materials as films is difficult or impossible as most of these polymers, with their rigid, conjugated structures, are brittle, infusible, and insoluble in most common solvents. All of this also makes them too expensive for most applications. Although intrinsically conducting polymers do not currently have the properties that would encourage their widespread use, improvements in synthesis, processing, and doping techniques will undoubtedly, yield improvements in the future.

Stacked One-Dimensional Conductors. Recently a number of stacked, one-dimensional conductors has been synthesized (17,18). This group comprises organic charge-transfer compounds such as TCNQ-TTF, tetracyano and bisoxalato platinates (Krogman salts), and macrocyclic ligand metal complexes. Conductivities of these compounds are typically in the range of $10^8\ \mu\Omega \cdot \text{cm}$ to $10^{10}\ \mu\Omega \cdot \text{cm}$. $(\text{TMTSF})_2\text{ClO}_4$ was the first organic compound found to be superconductive (1.3 K).

$[M(\text{phtalocyanine})\text{O}]_n$ polymers have been also synthesized, where M = Si, Ge, Sn converted to covalently linked, partially oxidized chain compounds. These materials have high environmental and thermal stability and are soluble without decomposition in strong acids. The polymers can be combined with Kevlar (DuPont) to produce robust processable, orientable fibers and when partially oxidized are good electrical conductors ($10^8\ \mu\Omega \cdot \text{cm}$ in stacking direction). However, conductivities indicate thermally activated (semiconducting) behavior.

Conductive Composites

Conductor-Loaded Dielectrics. Dielectric polymeric and ceramic materials, when loaded with conductive powders, fibers, or flakes, become good conductors of electricity and heat. The resulting composites are useful for a wide range of electrical interconnecting, electromagnetic shielding, electrostatic control, and radar-absorbing materials for radar stealth technology as well as thermal management applications.

Conducting properties of the composite vary significantly with the conductor dispersion, which is a function of particle loading, size, packing, and shape. A noncontact dispersion of particles leads to a basically insulating dielectric. If particles are in proximity, conduction is controlled by electron hopping and tunneling dependent on the electric field force. Studies indicate that gaps as large as 10 nm can be jumped. Particulates in physical contact form a random quasi-network in the matrix. Composites with a large-volume fraction of conductor show a linear, Ohm's-law-type, current-voltage relationship, though some nonlinearity due to electron hopping has been observed. Inclusion of a solid constituent into polymer matrices leads to processing problems as loading approaches the maximum volume fraction [for spheres, face-centered cubic (fcc) is 0.73, body-centered cubic (bcc) is 0.63, simple cubic (sc) is 0.53] and reduces the high strength and impact resistance of the plastics.

The dependence of conductance on the volume fraction of spherical particles is described by the percolation theory. Theories concerning nonspherical particles are sparse (19). At the percolation threshold, represented by the critical volume fraction of the conductor loading, a continuous electrical pathway is established, the resistivity of the composite drops sharply, and the composite becomes predominantly a conductor (20). Table 7 gives the critical volume fraction, V_c, for spherical silver particles in a phenolic resin.

V_c clearly falls with the particle size; 1 μm particles have a V_c of about 0.1 (10%), while nano-sized particles achieve a V_c below 0.01 (1%). It is important to note that V_c is also a function of the thickness and the length of the composite conductor. V_c increases with decreasing thickness and increasing length as the probability to form a continuous pathway is diminished.

Polymer Thick Film Inks. Polymer thick film (PTF) inks consist of thermoplastic (polycarbonates, polyethylene terephtalate) or thermosetting (epoxies, polyimides, phenolics) resins

Table 7. Critical Volume Fraction vs. Size

Size (μm)	V_c
1	~0.10
5	0.25
12	0.30
15	0.40
35	0.50

loaded with silver, copper, nickel, graphite, or inherently conductive polymers as the conductor phase (21–23). PTF inks are typically applied by silk screening or spray coating and can be processed below 200°C. Their main uses are electromagnetic interference (EMI) shielding coatings and specialized electrical interconnection applications in the printed circuit board (PCB) industry, such as conductive adhesives, via fill materials and resistors. Highly loaded silver inks can achieve conductivities of 1/20 that of bulk silver. A major issue with PTF inks, however, is that electrical properties may be compromised by temperature and humidity fluctuations, leading to oxidation of the particle surfaces and deterioration of particle-to-particle contacts due to polymer expansion. High conductor loadings required to achieve acceptable electrical conductivity can, in addition, lead to mechanical and adhesive failures.

Carbon-black-loaded polymer composites have uses as resistors and thermistors (temperature-dependent resistors). Resistive PTF inks are loaded with mixtures of carbon blacks and graphite, which are available with a range of conductivities. Low-resistance inks are obtained by addition of silver. Additives need to be balanced in such a way that the temperature coefficient of resistance (TCR) is as low as possible <300 ppm/°C. In contrast to resistors, thermistor materials have a very large negative (NTC) or positive (PTC) temperature coefficient of resistance. Thermistors are used as current limiters by becoming insulators at a certain temperature. Composite polymer-based thermistors have been made to improve ease of processing and to decrease room temperature resistivity compared to ceramic thermistors. Carbon-black polyethylene is the most widely used commercial composite thermistor type with resistivities around $10^6\ \mu\Omega \cdot \mathrm{cm}$. Fillers such as V_2O_2, TiB_2, and Ni in polyethlene have shown similar low room temperature resistivities with large PTCs.

Transient-Liquid-Phase-Sintering Polymer Composites. Transient-liquid-phase-sinterable (TLPS) (24) conductive composites were developed to overcome the shortcomings of PTF inks. TLPS pastes typically contain a metal, such as Cu, Ag, or Ni, and a solder-type component, such as SnPb or SnBi, together with a permanent polymeric adhesive binder. During heating (typically less than 220°C) the solder component temporarily melts, wets, diffuses, and reacts with the solid metal component to form a high-melting, intermetallic compound, such $CuSn_3$ or Cu_5Sn_6. Eventually a continuous, three-dimensional metallic web is formed, which does not remelt at the process temperature. Polymer-metallic TLPS composites are analogous to the ceramic-metallic (cermet) inks that have been used in hybrid circuit manufacturing for many years. TLPS composites do provide low bulk resistivity ($\rho = 25\ \mu\Omega \cdot \mathrm{cm}$), comparable to cermet materials, as well as very good environment stability and adhesive strength.

Conductor-Loaded Ceramics. Conductor-loaded ceramics include metals, graphite, and metal oxides as the conductive phase. While most ceramic-metallic composites, also known as cermets, are used for high-temperature structural applications, a subgroup is also widely used in ceramic thick film hybrid microcircuits. These types of cermets are applied in form of thick film inks, which are composed of an active component ($<5\ \mu$m fine metal powders, ceramic powders, metaloxides), a glassy binder (Pb-borosilicate glass, PbO, CuO, CdO), and an organic vehicle (ethyl cellulose). The thick film inks typically require processing temperatures above 850°C, at which the organic binder is burned out and the metal particles undergo sintering. Thick film conductors contain noble metals (Cu, Ag, Au, Pd, Pt) or refractory metals (Ni, Mo, W), achieving conductivities of 1/15 that of bulk silver. Thick film resistors contain thermally stable precious metal oxides, such as RuO_2 (RhO_2, IrO_2) and $Pb/Bi_2Ru_2O_7$, as conductive phase. Resistivities range from $10^6\ \mu\Omega \cdot \mathrm{cm}$ to $10^{12}\ \mu\Omega \cdot \mathrm{cm}$. Thermistors are usually made from doped ceramics such as barium titanate, which has a relatively high resistivity ($10^8\ \mu\Omega \cdot \mathrm{cm}$ $10^9\ \mu\Omega \cdot \mathrm{cm}$) and thus limits their use. Chromium doped vanadium sesquioxide, $(V,Cr)_2O_3$, has a lower resistivity ($10^3\ \mu\Omega \cdot \mathrm{cm}$), but properties are harder to control.

Table 8. Thermal Properties of Aluminum, Al/AlN, and Al/SiC

Material	Thermal Conductivity (W/m · °C)	Mean CTE (ppm/°C) 35–350°C	Density (g/cm^3)
Aluminum	212	25.2	2.697
Al/SiC (55.0 vol%)	126	12.0	2.979
Al/AlN (62.7 vol%)	129	11.1	3.019

Applications of cermets other than in microelectronics are copper graphite cermet contacts, which are noted for a minimum welding tendency in heavy-current circuit breakers. Because of their excellent resistance toward wear and arc erosion, cermets are also used for conductor-included ceramic contacts. Cadmium oxide–based cermets containing silver, nickel, or tungsten as the conductive phase are extensively used in low-voltage applications in tropical climates.

Metal Matrix Composites. Metal matrix composites, in particular aluminum matrix composites, have gained increased acceptance as substitutes for traditional electronic packaging materials. These materials can be reliably and cost-effectively fabricated by liquid infiltration of aluminum into a reinforcement matrix. They have a low coefficient of thermal expansion (CTE), high thermal and electrical ($< 40\ \mu\Omega \cdot \mathrm{cm}$) conductivity, and low density while providing increased strength (25). The low density makes aluminum matrix composites attractive for weight critical applications, such as in avionics or in portable electronic equipment (26). Recently, aluminum matrix composites (27) using aluminum nitride (AlN) have been shown to have properties equal to or superior to those of the more commonly used aluminum/silicon carbide (Al/SiC) composites (Table 8).

Intercalated Graphite. Because of its excellent conductance, graphite is considered to be a semimetal. Graphite has a layered structure with a 0.335 nm separation between layers, which can expand to accommodate larger guest atoms or molecules. In effect, the intercalants form charge transfer compounds although the exact nature of intercalation reaction is not entirely known. Intercalants may be divided into two groups: (1) alkali metals, which act as electron donors, and (2) proton acids (HNO_3), Lewis acids (metal halides), and halogens, which behave as electron acceptors.

Graphite intercalated with potassium, rubidium, or cesium becomes metallic and exhibits superconductivity below 1 K.

The bronze red C_8K is prepared by evaporation of potassium at 300°C in the presence of graphite. All alkali metal graphites are extremely reactive with air and water. When intercalated with AsF_5, graphite also becomes metallic, showing a conductivity even somewhat higher than copper. Potential applications for intercalated graphite are EMI shielding or wiring for use in power transmission, aircraft electronic systems, or internal carriers in transformers or motors. In the laboratory, a composite has been formed by enclosing powdered intercalated graphite into a copper matrix (one third copper) and swaging it into wires. Other intercalated materials are being investigated, notably intercalated boron nitride, which has a similar structure to graphite.

Loosely related to graphite are the buckminsterfullerenes. Alkali salts of buckminsterfullerene, a soccer ball–shaped C_{60} allotrope of carbon, have been a recent addition to the superconducting family. For instance, a T_c of 18 K has been reported for thin films of K_3C_{60} and a T_c of 30 for Rb_3C_{60}.

Solid Electrolytes

"Fast" Ion Conductors. Migration of ions does not occur to any appreciable extent in most ionic and covalent solids, such as oxides and halides. Only at high temperatures, where the defect concentrations become quite large and the atoms have a lot of thermal energy, does the conductivity become appreciable. The conductivity of NaCl at 800°C (just below its melting point) is about $10^9\ \mu\Omega \cdot \mathrm{cm}$, whereas at room temperature it is an insulator. In contrast, there exists a small group of ionic solids called solid electrolytes, superionic conductors, or fast ion conductors (28,29), in which one set of ions can move easily. Such materials often have special crystal structures, such as open tunnels or layers through which the mobile ions may move. The critical temperature at which abrupt transition to high electrical conductivity ($10^3\ \mu\Omega \cdot \mathrm{cm}$ to $10^6\ \mu\Omega \cdot \mathrm{cm}$) occurs is also called the α-phase to β-phase transition. This temperature is well above 300 K for typical solid electrolytes such as AgI, $LiZr_2PO_4$, Li_3N, and $Li_3B_7O_{12}S$. Principal charge carriers are cations and anions, while the contribution of electrons is very small. Conduction in solid electrolytes is sustained by defects in the crystalline structure.

Point defects allow thermally induced ionic transport through Frenkel (or Schottky) defect pairs. Hence, the number of defects and the proportionate number of charge carriers are functions of temperature, requiring an activation energy in excess of 1 eV. A defect concentration on the order of $10^{20}/\mathrm{cm}^3$ is useful for fast ion conductors.

Molten sublattice defects correspond to insufficient sites in the sublattice region for the available ions to occupy them. This results in ionic hopping or free-ion movement from one available site to the other. This process allows all the ions to participate in the conduction phenomenon with the result that the activation energy is rather low. The mobile ions as charge carriers amount to nearly $10^{23}/\mathrm{cm}^3$. The material is a liquid-like molten sublattice, often realized via channeled or layered structures.

Solid electrolytes are applied in engineering applications such as fuel cells (Mn-doped cobalt chromite, Ni, or Co-zirconia cermets), solid-state batteries (AgI, LiI, $Na_2O{-}Al_2O_3$), coulombmeters (AgBr, $RbAg_4I_5$), electrochemical capacitors (AgI, AgBr, $RbAg_4I_5$), and oxygen sensors (Ca stabilized zirconia, CSZ). β-Alumina has been pioneered by the Ford Motor company for high-density energy storage systems. β-Alumina is a misnomer for $M_2O{-}nX_2O_3$, where n is 5 to 11, M is a monovalent cation, and X is a trivalent cation. Resistivity for the Na^+ ion in $Na_2O{-}5Al_2O_3$ at 25°C is comparable to strong liquid electrolytes ($< 10^9\ \mu\Omega \cdot \mathrm{cm}$).

Conducting Polymer Salt Complexes. Another class of electrical conductors are the polymer salt complexes, also termed polymer ion electrolytes or ionomers (30). These materials where first developed for ion-exchange applications and are only superficially related to the organic polymeric conductors. Although some doped conducting polymers may be considered to be polymer-ion-type conductors, their conduction mechanism involves primarily solitons, polarons, or bipolarons. Very much in contrast to this, the conduction mechanism in the polymer-ion-type conductors involves ion conduction.

The electrical conductivities of the polymer ion electrolytes are similar to the values obtained for semiconductors, while the doped polymer conductors manifest as much as seven orders of magnitude higher conductivities. Typical examples for polymer salt complexes are polyethylene oxide (PEO) and polypropylene oxide (PPO) polymers complexed with alkali-metal salts. Conductivity depends mainly on the mobile cations, which move through helical tunnels formed by the polymer backbone. Anions are thought to block conductivity by ion pairing. The most crystalline salts demonstrate the highest conductivities. PEO-based electrolytes can generally attain conductivities on the order of $10^{11}\ \mu\Omega \cdot \mathrm{cm}$; although a PEO-based network incorporationg $LiClO_4$ was reported to reach a room temperature conductivity of $7.7 \times 10^9\ \mu\Omega \cdot \mathrm{cm}$. Polymer electrolytes are pliable and deform under stress. Because of their low weight and volume, they may find uses as electrolytes in solid-state, high-energy-density batteries, fuel cells, and sensors.

Molecular Scale Electronics

If the current trend in size reduction in electronic devices is maintained, sometime in the first half of the twenty-first century the molecular scale will be reached (31). Doped polyacetylene—a quasi-molecular wire—marked the early beginnings. Since then the prospects for progress toward molecular scale electronics has much improved as scientific developments have provided the means to explore and manipulate properties of molecular systems at the molecular level using scanning tunneling (STM) and atomic force (AFM) microscopy or related techniques.

The ability of biomacromolecules to self-assemble into higher-order supramolecular structures with specific functionalities has prompted chemists to explore synthetic methods of self-assembly. Molecular self-assembly can be considered as a means of producing nanometer-scale structures in a reproducible manner without recourse to lithography. A variety of approaches have been developed that provide molecules trapped in molecular cages, interlocked ring molecules, and rings on linear molecular chains. Highly efficient electron transfer can occur in biomolecules such as bacteriorhodopsin. Surface modification of the molecule enables the electron transfer to be directed to external electrodes.

Ion transport through ion channels in membranes is well known and would be another way of molecular scale communication. It could be controlled by applied voltages and chemicals. Simple channels can be, for instance, formed from specialized peptides. Since many ions can go through these ion gates, this would open the possibility of fanouts from one gate to many.

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