15.1 Introduction and synopsis

York Minster, constructed between 1220 and 1400, is one of the great cathedrals of Europe. Many fine sermons have been preached from its pulpit, but when, in 1984, the Archbishop of York expressed his disbelief in the Virgin Birth, the Minster was struck by lightning and severely damaged. Some put this down to the wrath of God, but the reality is simpler – the cathedral was inadequately grounded (earthed). There is a message here: even when you are designing cathedrals, electrical properties matter.

This chapter is about the simplest of these: properties relating to conduction, insulation, and dielectric behaviour. *Electrical conduction* (as in lightning conductors) and *insulation* (as in electric plug casings) are familiar properties. Superconductivity, semiconduction, and dielectric behaviour may be less so. *Superconductivity* is the special characteristic of some materials to lose all resistance at very low temperatures so that a current flows without loss. *Semiconductors*, the materials of transistors and silicon chips, fall somewhere between conductor and insulator, as the name suggests. A *dielectric* is an insulator. It is usual to use the word 'insulator' when referring to its inability to conduct electricity and to use 'dielectric' when referring to its behaviour in an electric field. Three properties are of importance here. The first, the *dielectric constant* (or *relative permittivity*), describes the way a material acquires a dipole moment (it *polarises*) in an electric field. The second, the *dielectric loss factor*, measures the energy dissipated when radio-frequency waves pass through a material, with the energy appearing as heat (the principle of microwave cooking). The third is the *dielectric breakdown potential*, and this takes us back to York Minster. Lightning is a form of dielectric breakdown, which can be just as damaging on a small scale – in a piece of electrical equipment, for example – as on a large one.

There are many different kinds of electrical behaviour, all of them useful. Figure 15.1 gives an overview, with examples of materials and applications. This chapter introduces electrical properties and their physical origins, and gives examples of design for electrical performance.

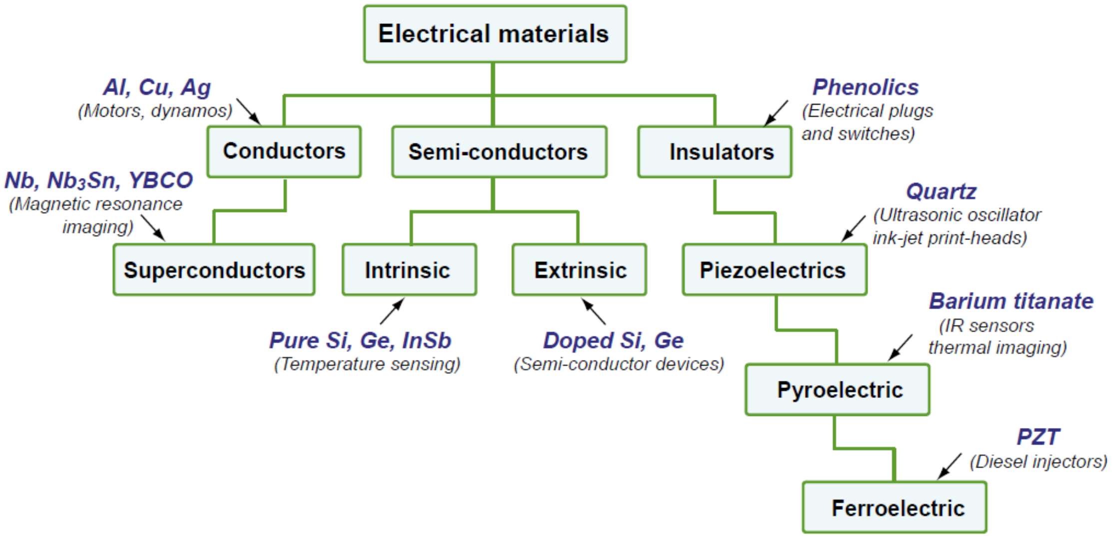

Figure 15.1 The hierarchy of electrical behaviour, with examples of materials and applications. Their nature and origins are described in this chapter.

15.2 Conductors, insulators, and dielectrics

Resistivity and conductivity The electrical resistance R (units: ohms[1], symbol Ω) of a rod of material is the potential drop V (Volts[2]) across it, divided by the current i (A, or amps[3]) passing through it, as in Figure 15.2. This relationship is Ohm's law:

$$R = \frac{V}{i} \tag{15.1}$$

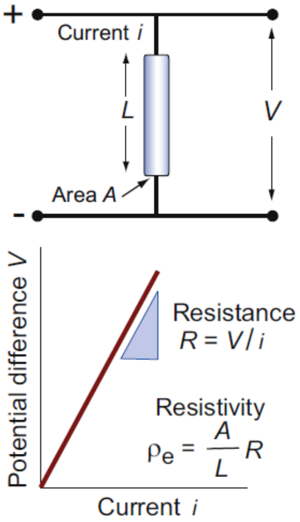

Figure 15.2 Measuring electrical resistivity.

Resistance also determines the power P dissipated when a current passes through a conductor (measured in Watts[4]):

$$P = i^2 R \tag{15.2}$$

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[1] George Simon Ohm (1789–1854), dropped out of his studies at the University of Erlangen, preferring billiards to mathematics, but later became absorbed in the theory of electricity and magnetism.

[2] Alessandro Guiseppe Antonio Anastasio Volta (1745–1827), Italian physicist, inventor of the battery, or as it was then known, the Voltaic Pile. His face used to appear on the 10,000 lire note.

[3] André Marie Ampère (1775–1836), French mathematician and physicist, largely self-taught and said to have mastered all known mathematics by the age of 14. His life was not a happy one: his father was guillotined during the French revolution, and he was miserably married and had difficult children – yet he remained extensively productive up to his death, contributing to the theories of electricity, light, magnetism, and chemistry (he discovered fluorine).

[4] James Watt (1763–1819), instrument maker and inventor of the steam engine (the idea came to him whilst 'walking on a fine Sabbath afternoon'), which he doggedly developed. Unlike so many of the footnoted characters of this book, Watt, in his final years, was healthy, happy, and famous.

The material property that determines resistance is the *electrical resistivity*, ρ_e. It is related to the resistance by

$$\rho_e = \frac{A}{L} R \tag{15.3}$$

where A is the section and L the length of a test rod of material – think of it as the resistance between opposing faces of a unit cube of the material. Its units in the metric system are Ω.m, but it is commonly reported in units of μΩ.cm. It has an immense range, from a little more than 10^{-8} in units of Ω.m for good conductors (equivalent to 1 μΩ.cm, which is why these units are still used) to more than 10^{16} Ω.m (10^{24} μΩ.cm) for the best insulators. The electrical conductivity κ_e is simply the reciprocal of the resistivity. Its units are siemens per metre (S/m or $(\Omega.\mathrm{m})^{-1}$).

Temperature-dependence of resistivity The resistivity ρ_e of metals increases with temperature because thermal vibrations scatter electrons. Incandescent lamps (now rare) depend on this; as the filament heats, its resistance rises, and this stabilises the temperature at a value that does not cause burn-out. The resistivity of semiconductors, by contrast, decreases as temperature increases, because thermal energy allows more carriers to cross the band gap, entering the conduction band (explained later). Some materials, though, behave in a more dramatic way.

Superconducting materials suddenly lose all resistance at a critical temperature, T_c, above 0K. Below T_c, the current in a superconducting material flows without any resistive loss; above T_c, superconductivity is suppressed. An applied magnetic field H lowers the temperature at which superconduction starts, and a field greater than the zero-Kelvin critical field $H_{c,o}$ suppresses it completely.

Any electrical current induces a magnetic field. Thus the existence of a critical field implies an upper-limiting current density that can by carried by the superconductor before its own field quenches the superconduction. The critical temperatures and fields of superconducting materials are plotted in Figure 15.3. Many pure metals become superconducting, though only at very low temperatures, and all have low critical fields, too low to be of much practical use. The intermetallic compounds Nb_3Sn, NbTi, Nb_3Ge, and Nb_3Al have higher critical temperatures and fields – high enough to be practical for MRI scanners and superconducting energy storage. In 1986 a third class of superconductor was discovered with critical temperatures and fields that were higher still. They are (surprisingly) ceramics, exhibiting high resistivity at room temperature yet superconducting at temperatures as high as 130K. This is significant because it is above the boiling point of liquid nitrogen, a cheap and widely available refrigerant, making superconducting devices practical and economic. The most widely used at present is the oxide ceramic $YBa_2Cu_3O_7$ ('YBCO'), used in high-field magnets, magnetic resonance imaging and mag-lev trains.

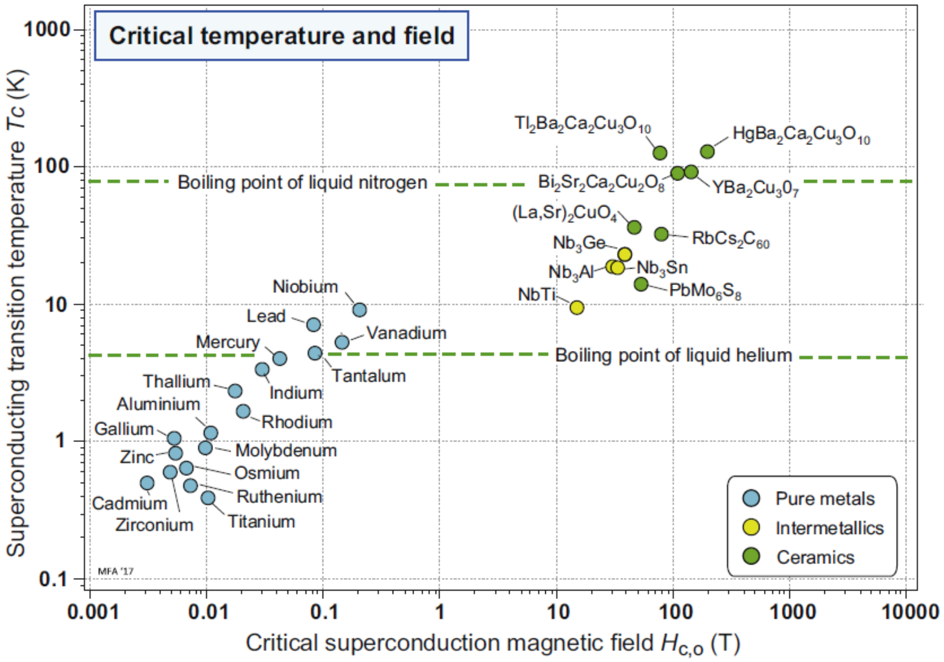

Figure 15.3 The critical fields and temperatures for metallic and ceramic superconductors. Note the boiling points of liquid nitrogen and helium.

Dielectric properties An *electric field*, *E*, *is* a region of space in which charged objects experience a force. The electric field strength between two oppositely charged plates separated by a distance *t* and with a potential difference *V* between them is

$$E = \frac{V}{t} \tag{15.4}$$

and is independent of position except near the edge of the plates.

Two conducting plates separated by a dielectric make a *capacitor* (Figure 15.4). Capacitors (or *condensers*) store charge. The charge Q (coulombs[5]) is directly proportional to the voltage difference between the plates, V (Volts):

$$Q = CV \tag{15.5}$$

where C (farads[6]) is the capacitance. The capacitance of a parallel plate capacitor of area A and spacing t, separated by empty space (or by air) is

$$C = \varepsilon_o \frac{A}{t} \tag{15.6}$$

where ε_o is the *permittivity of free space* (8.85×10^{-12} F/m, where F is farads). If the empty space is replaced by a dielectric, the dielectric *polarises* and the capacitance increases. The field created by the polarisation opposes the field E, reducing the voltage difference V needed to support the charge. Thus the capacitance of the condenser is increased to the new value

$$C = \varepsilon \frac{A}{t} \tag{15.7}$$

where ε is the *permittivity of the dielectric* with the same units as ε_o. It is usual to cite not this but the *relative permittivity* or *dielectric constant*, ε_r:

$$\varepsilon_r = \frac{C_{\text{with dielectric}}}{C_{\text{no dielectric}}} = \frac{\varepsilon}{\varepsilon_o} \tag{15.8}$$

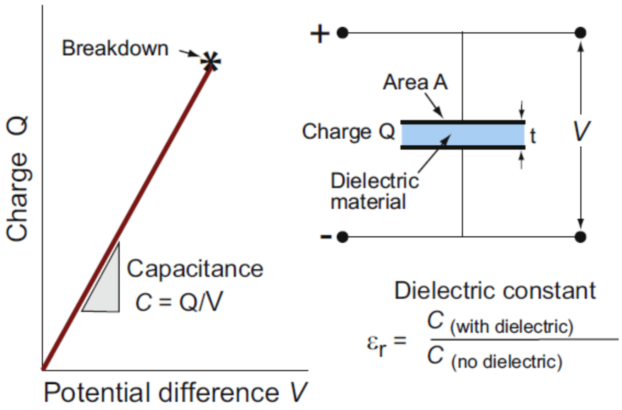

Figure 15.4 Dielectric constant and dielectric breakdown.

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[5] Charles Augustin Coulomb (1736–1806), military physicist, laid the foundations of both the mathematical description of electrostatic forces and the laws of friction. Despite his appointment as Intendant des Eaux et Fontaines de Paris, he made no known contributions to hydrodynamics.

[6] Michael Faraday (1791–1867), brilliant experimentalist both in physics and chemistry, discoverer of electromagnetic induction and inspiring lecturer at the Royal Institution, London.

making the capacitance

$$C = \varepsilon_r \varepsilon_o \frac{A}{t} \tag{15.9}$$

Being a ratio, ε_r is dimensionless. Its value for empty space, and for practical purposes for most gases, is 1. Most dielectrics have values between 2 and 20, though low-density foams approach the value 1 because they are largely air. Ferroelectrics are special: they have values of ε_r as high as 20,000. We return to ferroelectrics later in this chapter.

Capacitance is one way to measure the dielectric constant of a material (Figure 15.4). The charge stored in the capacitor is measured by integrating the current that flows into it as the potential difference V is increased. The ratio Q/V is the capacitance. The dielectric constant ε_r is calculated from equation (15.8).

Small capacitors, with capacitances measured in micro-farads (μF) or pico-farads (pF), are used in resistor-capacitor (R-C) circuits to tune oscillations and give controlled time delays. The time constant for charging or discharging a capacitor is

$$\tau = RC \tag{15.10}$$

where R is the resistance of the circuit. When charged, the energy stored in a capacitor is

$$E_c = \frac{1}{2} QV = \frac{1}{2} CV^2 \tag{15.11}$$

'Super-capacitors', with capacitances measured in farads, store enough energy to power a hybrid car.

The *charge density*, D (units coulombs/m^2), on the surface of a dielectric in a field E is

$$D = \varepsilon_r \varepsilon_o E \tag{15.12}$$

where E is the electric field (voltage across the dielectric divided by its thickness).

The *breakdown field* or *dielectric strength of a dielectric*, E_b (units: V/m or more usually MV/m), is the electrical field gradient at which an insulator breaks down and a damaging surge of current flows through it. It is measured by increasing, at a uniform rate, a 60-Hz alternating potential applied across the faces of a plate of the material in a configuration like that of Figure 15.4 until breakdown occurs, typically at a potential gradient between 1 and 100 MV/m. The maximum charge density that a dielectric can carry is thus when the field is just below its breakdown field:

$$D_{max} = \varepsilon_r \varepsilon_o E_b \tag{15.13}$$

and the maximum energy density is

$$\frac{1}{2} \frac{CV^2}{A\,t} = \frac{1}{2} \varepsilon_r \varepsilon_o E_b^2 \tag{15.14}$$

The *loss tangent* and the *loss factor* take a little more explanation. We shall see in Section 15.4 that polarisation involves the small displacement of charge (either of electrons or of ions) or of molecules that carry a dipole moment when an electric field is applied. An oscillating field drives the charge between two alternative configurations. This charge-motion is like an electric current that – if there were no losses – would be 90 degrees out of phase with the voltage. In real dielectrics, this current dissipates energy just as a current in a resistor does, giving it a small phase shift, δ, between the voltage and current (Figure 15.5). The *loss tangent*, tan δ, or *dissipation factor*, D_f, is the tangent of the loss angle. The power factor, P_f, is the sine of the loss angle. When δ is small, as it is for the materials of interest here, all three are essentially equivalent:

$$\tan\delta \approx \sin\delta \approx P_f \approx D_f \tag{15.15}$$

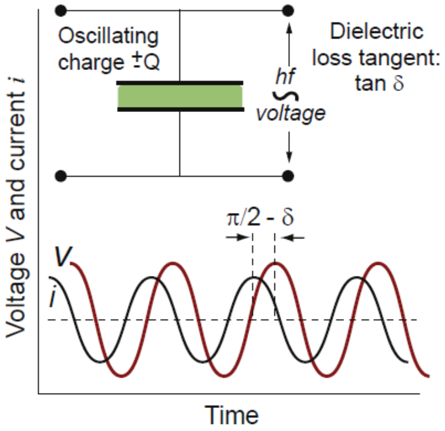

Figure 15.5 Dielectric loss.

More useful, for our purposes, is the *loss factor* L, which is the loss tangent times the dielectric constant:

$$L = \varepsilon_r \tan\delta \tag{15.16}$$

It measures the energy dissipated by a dielectric when in an oscillating field. If you want to select materials to minimise or maximise dielectric loss, then the measure you want is L.

When a dielectric material is placed in a cyclic electric field of amplitude E and frequency f, power P is dissipated, and the field is correspondingly attenuated. The power dissipated per unit volume, in W/m^3, is

$$P \approx f\,E^2\varepsilon\tan\delta = f\,E^2\varepsilon_o\varepsilon_r\tan\delta \tag{15.17}$$

This power appears as heat and is generated uniformly (if the field is uniform) through the volume of the material. Thus the higher the frequency and field strength, and the greater the loss factor $\varepsilon_r \tan\delta$, the greater the heating and energy loss. Dielectric loss is the basis of microwave cooking and is exploited in materials processing – the radio-frequency welding of polymers is an example.

All dielectrics change shape in an electric field, a consequence of the small shift in charge that allows them to polarise; the effect is called *electrostriction*. Electrostriction is a one-sided relationship in that an electric field causes deformation, but deformation does not produce an electric field. *Piezoelectric* materials, by contrast, display a two-sided relationship between polarisation and deformation: a field induces deformation, and deformation induces charge differences between its surfaces, thus creating a field. The piezoelectric coefficient is the strain per unit of electric field, and although it is very small, it is a true linear effect, and this makes it useful – when you want to position or move a probe with nano-scale precision, it is just what you need. *Pyroelectric* materials contain molecules with permanent dipole moments that in a single crystal are aligned, giving the crystal a permanent polarisation. When the temperature is changed, the polarisation changes, creating surface charges, or if the surfaces are connected electrically, a pyroelectric current – the principle of intruder-detection systems and of thermal imaging. *Ferroelectric* materials, too, have a natural dipole moment; they are polarised to start with, and the individual polarised molecules line up so that their dipole moments are parallel. Their special feature is that the direction of polarisation can be changed by applying an electric field, and the change causes a change of shape. Applications of all of these are described in Section 15.5.

15.3 Charts for electrical properties

All materials have an electrical resistivity, and all dielectrics have a dielectric constant and loss factor. Property charts for these allow comparison between a large and varied population.

Thermal conductivity and electrical resistivity Figure 15.6 shows the thermal conductivity λ and the electrical conductivity κ_e. The first has a range of 10^5, the second a range of 10^{28}; no other material property has such a wide range. For metals, thermal and electrical conduction are linked because both depend on free electrons, giving the obvious correlation between the two at the upper right of the chart,

$$\kappa_e \approx 10^5 \lambda \tag{15.18}$$

(λ in W/m.K, κ_e in S/m), a relationship known as the Wiedemann–Franz law.

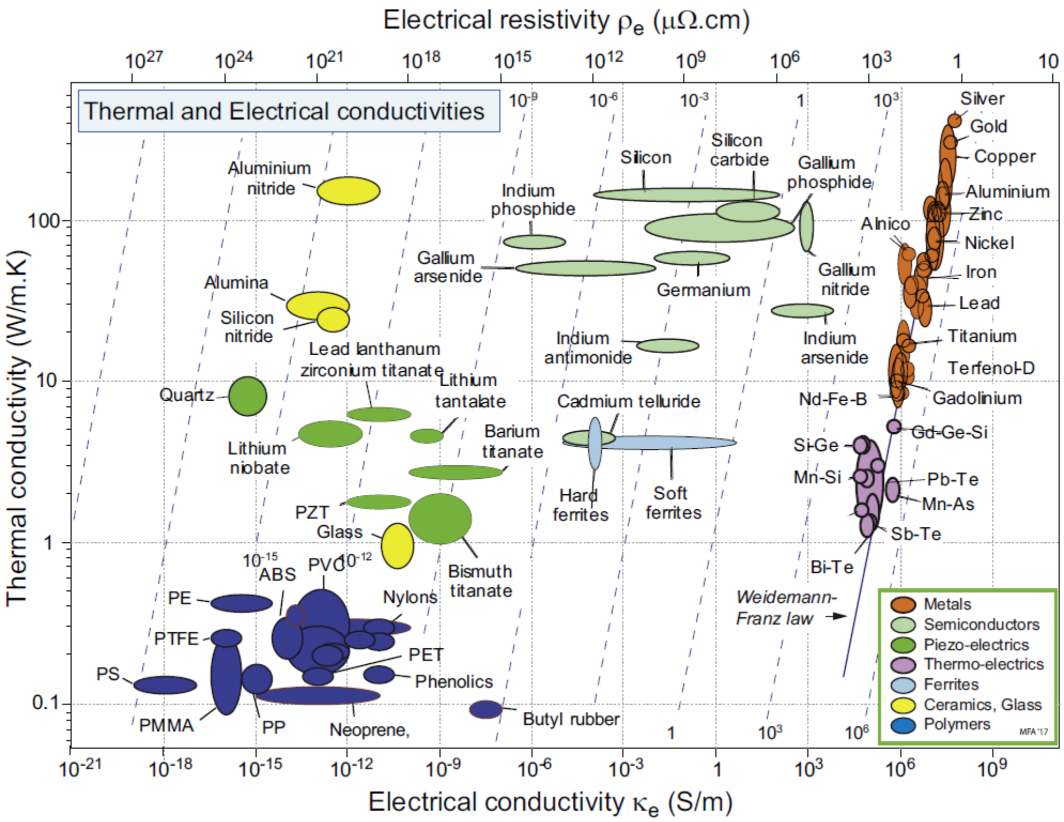

Figure 15.6 Chart of thermal conductivity, λ against electrical conductivity, κ_e; the electrical resistivity ρ_e is the reciprocal of the conductivity and is shown across the top.

Dielectric constant, dielectric breakdown, and limiting electric energy density The chart of Figure 15.7 gives an overview of dielectric behaviour. Molecules containing polar groups, such as nylon, polyurethane, and ionic-bonded ceramics, react strongly to an electric field and polarise, giving them high dielectric constants. Those with purely covalent or Van der Waals bonding do not polarise easily and have low values. The dielectric strengths differ too – polymers have higher values than ceramics or glasses. The contours show values of the upper limiting energy density $\frac{1}{2}\varepsilon_r \varepsilon_o E_b^2$, where ε_o is the permittivity of vacuum, 8.85×10^{-12} F/m (equation (15.14)). Ferroelectric ceramics stand out due to their high dielectric constants.

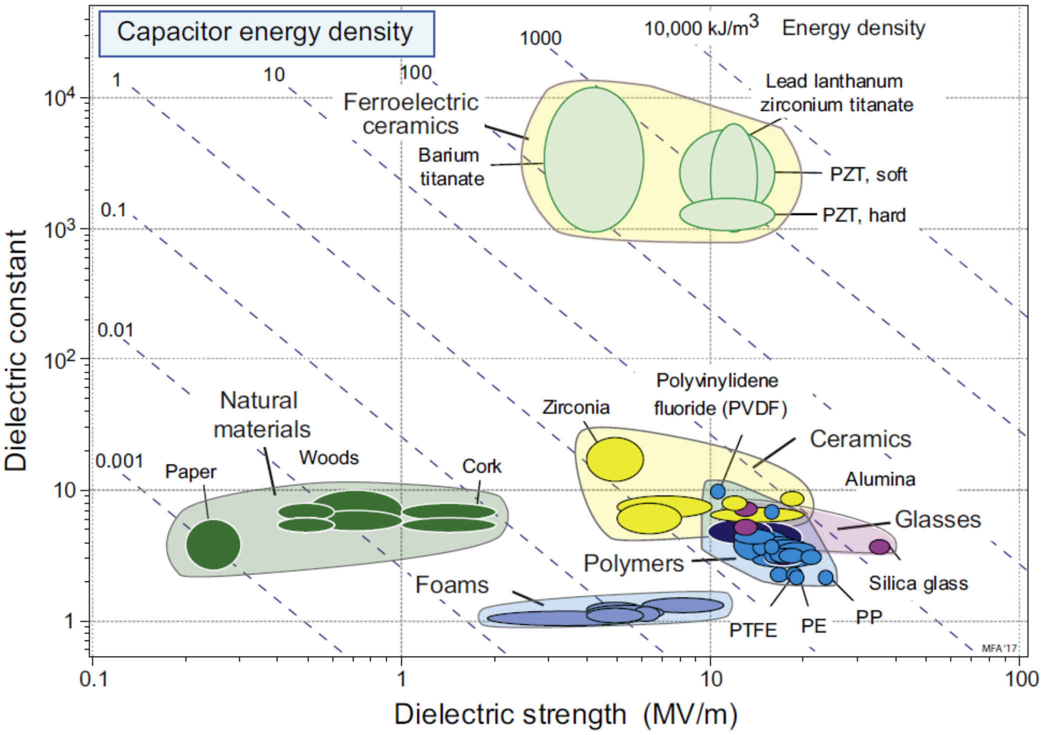

Figure 15.7 The dielectric properties of materials.

15.4 Drilling down: the origins and manipulation of electrical properties

Electrical conductivity Solids are made up of atoms containing electrons that carry a charge $-e$ and a nucleus containing protons, each with a positive charge $+e$. An electric field, E (volts/m), exerts a force $E.e$ on a particle carrying a charge e. If the charge-carriers can move, the force $E.e$ causes them to flow through the material — that is, it conducts. Metals are *electron-conductors*, meaning that the charge-carriers are the electrons. In ionic solids (which are composed of negatively and positively charged ions like Na^+ and Cl^-), the diffusive motion of ions allows *ionic conduction*, but this is only possible at temperatures at which diffusion is rapid. Many materials have no mobile electrons, and at room temperature they are too cold to be ionic conductors. The charged particles they contain still feel a force in an electric field that displaces the charges slightly, but they are unable to move more than a tiny fraction of the atom spacing. These are insulators; the small displacement of charge gives them dielectric properties.

Chapter 4, Section 4.5 explained the way electrons of an atom occupy discrete energy states or orbits, arranged in shells (designated 1, 2, 3, etc. from innermost to outermost); each shell is made up of sub-shells (designated s, p, d, and f), each of which contains 1, 3, 5, or 7 orbits respectively. The electrons fill the shells with the lowest energy, two electrons of opposite spin in each orbit; the *Pauli*[7] *exclusion principle* prohibits an energy state with more than two. When *n* atoms (a large number) are brought together to form a solid, the inner electrons remain the property of the atom on which they started, but the outer ones interact. Each atom now sits in the field created by the charges of its neighbours. This has the effect of decreasing slightly the energy levels of electrons spinning in a direction favoured by the field of its neighbours and raising that of those with spins in the opposite direction, splitting each energy level. Thus the discrete levels of an isolated atom broaden in the solid into *bands* of very closely spaced levels. The number of electrons per atom depends only on the atomic number; they fill the bands from the bottom, starting from the lowest, until all are on board, so to speak. The topmost filled energy level at 0K is called the Fermi[8] energy (more on this later).

Above 0K, thermal energy allows electrons to occupy higher levels with a certain probability; the Fermi level is then defined as the energy level having the probability that it is exactly half filled with electrons. Levels of lower energy than the Fermi level tend to be entirely filled with electrons, whereas energy levels higher than the Fermi tend to be empty. If two materials with different Fermi levels are placed in contact, electrons flow from the material with the higher Fermi level into the one with the lower Fermi level, creating a charge difference between them. The electric field associated with this charge difference raises the lower Fermi level and lowers the higher Fermi level until the two are equal.

An electron at the Fermi level still has an energy that is lower than it would have if it were isolated in vacuum far from the atoms. This energy difference is called, for historical reasons, the *work function*, because it is the work that is required to remove an electron from the Fermi level to infinity. If you want to create an electron beam, it can be done by heating the metal until some of its electrons have enough energy to exceed the work function, then accelerating them away with a field gradient.

Whether the material is a conductor or an insulator depends on how full the bands are and whether they overlap. In Figure 15.8, the central column describes an isolated atom, and the outer ones illustrate the possibilities created by bringing atoms together into an array, with the energies spread into energy bands. Conductors like copper, shown on the left, have an unfilled outer band; there are many very closely spaced levels just above the last full one, and when accelerated by a field, electrons can use these levels to move freely through the material. In insulators, shown on the right, the outermost band with electrons in it is full, and the nearest empty band is separated from it in energy by a wide *band gap*. Semiconductors, too, have a band gap, but it is narrower – narrow enough that thermal energy can pop a few electrons into the empty band, where they conduct. Deliberate doping (adding trace levels of other elements) creates new levels in the band gap, reducing the energy barrier to entering the empty states and thus allowing more carriers to become mobile.

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[7] Wolfgang Joseph Pauli (1900–1958), quantum theorist, conceiver of the neutrino and Nobel Prize winner. He was not, however, a happy man, requiring psychotherapy, which he received from none other than the great psychoanalyst Karl Jung.

[8] Enrico Fermi (1901–1954), devisor of the statistical laws known as Fermi statistics governing the behaviour of electrons in solids. He was one of the leaders of the team of physicists on the Manhattan Project for the development of the atomic bomb.

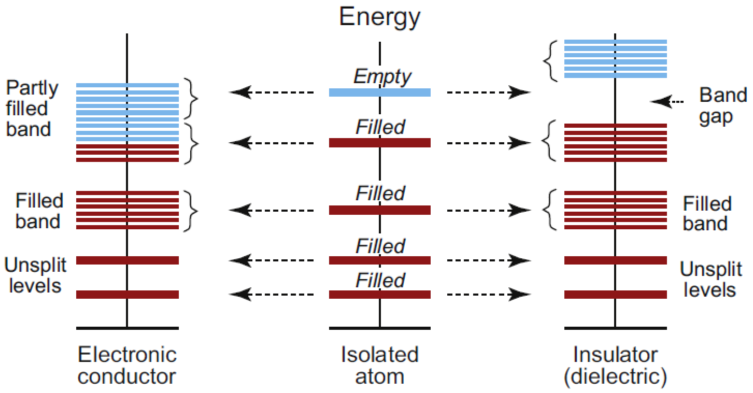

Figure 15.8 Conductors (left) have a partly filled outer band. Insulators (right) have a filled outer band, separated from the nearest unfilled band by a band gap.

Electrical resistance If a field E exerts a force $E.e$ on an electron, why does it not accelerate forever, giving a current that continuously increases with time? This is not what happens; instead, switching on a field causes a current that almost immediately reaches a steady value. Referring back to equations (15.1) and (15.3), the current density i/A is proportional to the field E,

$$\frac{i}{A} = \frac{E}{\rho_e} = \kappa_e E \tag{15.19}$$

where ρ_e is the resistivity and κ_e, its reciprocal, is the electrical conductivity.

Broadly speaking, the picture is this. Conduction electrons are free to move through the solid. Their thermal energy kT (k = Boltzmann's constant, T = absolute temperature) causes them to move like gas atoms in all directions. In doing this they collide with *scattering centres*, bouncing off in a new direction. Impurity or solute atoms are particularly effective scattering centres (which is why alloys always have a higher resistivity than those of pure metals), but electrons are scattered also by imperfections such as dislocations and by the thermal vibration of the atoms themselves. When there is no field, there is no *net* transfer of charge in any direction even though all the conduction electrons are moving freely. A field causes a drift velocity $v_d = \mu_e E$ on the electrons, where μ_e is the electron mobility, and it is this that gives the current (Figure 15.9). The drift velocity is small compared with the thermal velocity; it is like a breeze in air – the thermal motion of the air molecules is far greater than the 'drift' that we feel as the breeze. The greater the number of scattering centres, the shorter the mean-free path, λ_{mfp}, of the electrons between collisions, and the slower, on average, they move. Just as with thermal conductivity, the electrical conductivity depends on a mean-free path, on the density of carriers (the number n_v of mobile electrons per unit volume), and the charge they carry. Thus the current density, i/A, is given by

$$\frac{i}{A} = n_v e v_d = n_v e \mu_e E$$

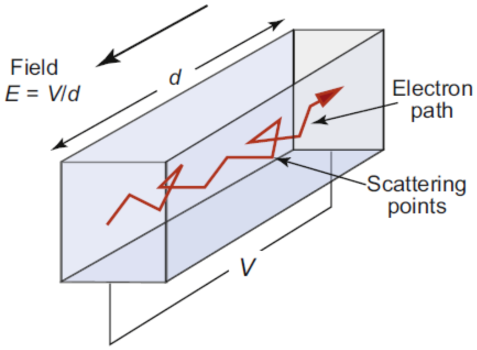

Figure 15.9 An electron, accelerated by the field E, is scattered by imperfections that create a resistance to its motion.

Comparing this with equation (15.19) gives the conductivity:

$$\kappa_e = n_v\, e\, \mu_e \tag{15.20}$$

Thus the conductivity is proportional to the density of free electrons and to the drift velocity, and this is directly proportional to the mean-free path. The purer and more perfect the conductor, the higher the conductivity and the lower its reciprocal, the resistivity.

Metals are strengthened (Chapter 7) by solid-solution hardening, work hardening, or precipitation hardening. All of these change the resistivity too. Figure 15.10 shows how the strength and resistivity of copper and aluminium are changed by alloying and deformation. Adding solute to either metal increases its strength, but the solute atoms also act as scattering centres, increasing the electrical resistivity as well. Dislocations add strength (by what we called *work hardening*), and they too scatter electrons a little, though much less than solutes do. Precipitates offer the greatest gain in strength; their effect on resistivity varies, depending on their size and spacing compared to the electron mean-free path and on the amount of residual solute left in the lattice. Precipitation hardening (with low residual solute) and work hardening are therefore the best ways to strengthen conductors. The two figures show that commercial conductor alloys have much greater strength and only slightly greater resistivity than those of the pure metals.

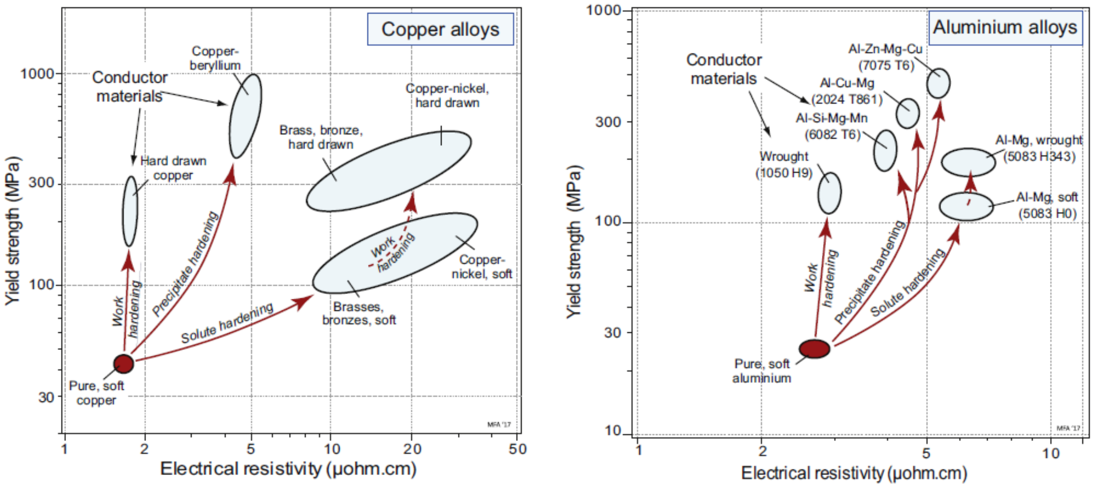

Figure 15.10 Strengthening mechanisms increase resistivity. Work hardening and precipitation do so less than solute hardening, as seen here in copper and aluminium alloys.

The resistivity of metals increases with temperature because thermal vibrations (phonons) scatter electrons. Resistance decreases as temperature falls, which is why very high-powered electromagnets are pre-cooled in liquid nitrogen. As absolute zero is approached, most metals retain some resistivity, but as discussed earlier, a few suddenly lose all resistance and become superconducting between 0 and 10K. The resistivity of semiconductors, by contrast, decreases as temperature increases for reasons explained next.

Semiconductors Semiconductors are based on elements in which four valence electrons fill the valence band, with an energy gap separating them from the next available level (in the conduction band). They get their name from their electrical conductivities, 10^{-4} to 10^{+4} (S/m), much smaller than those of metals but still much larger than those of insulators. At 0K, pure semiconductors are perfect insulators because there are no electrons in their conduction band. The band gap, however, is narrow, allowing thermal energy to excite electrons from the valence to the conduction band at temperatures above 0K and leaving holes behind in the valence band. The electrons in the conduction band are mobile and move in an electric field, carrying current. The holes in the valence band are also mobile (in reality it is the electrons in the valence band that move cooperatively, allowing the hole to change position), and this charge movement also carries current. Thus the conductivity of a semiconductor has an extra term

$$\kappa_e = n_v \, e \, \mu_e + n_h \, e \, \mu_h \tag{15.21}$$

where n_h is the number of holes per unit volume and μ_h is the hole mobility. In pure semiconductors, each electron promoted to the conduction band leaves a hole in the valence bend, so $n_e = n_h$, the conductivity becomes

$$\kappa_e = n_v \, e \, (\mu_e + \mu_h) \tag{15.22}$$

and the semiconduction is said to be *intrinsic* (a fundamental property of the pure material).

The number of charge carriers can be controlled in another way, by doping with controlled, small additions of elements that have a different valence than that of the semiconductor itself. This creates free electrons and holes that simply depend on the concentration of dopant, and the semiconducting behaviour is said to be *extrinsic* (a characteristic of the doping rather than of the base material).

Dielectric behaviour In the absence of an electric field, the electrons and protons in most dielectrics are symmetrically distributed and the material carries no net charge or dipole moment. In the presence of a field, the positively charged particles are pushed in the direction of the field, and negatively charged particles are pushed in the opposite direction. The effect is easiest to see in ionic crystals, since here neighbouring ions carry opposite charges, as on the left of Figure 15.11. Switch on the field and the positive ions (charge $+q$) are pulled in the field direction, the negative ones (charge $-q$) in the reverse, until the restoring force of the inter-atomic bonds just balances the force due to the field at a displacement of Δx, as on the right of the figure. Two charges $\pm q$ separated by a distance Δx create a dipole with dipole moment, d, given by

$$d = q\,\Delta x \tag{15.23}$$

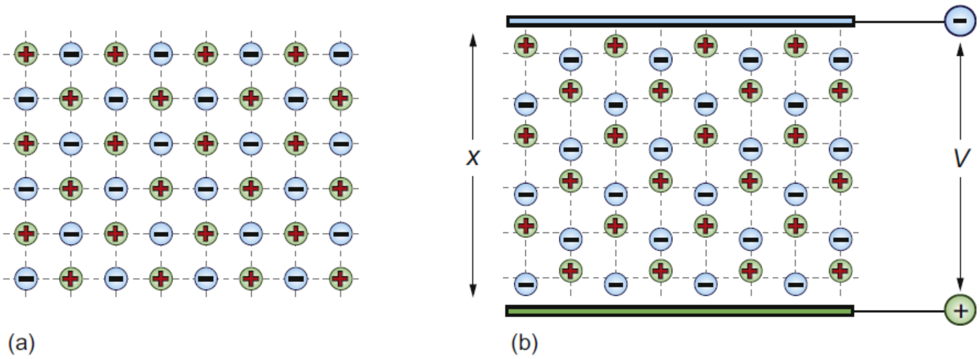

Figure 15.11 An ionic crystal (a) in zero applied field, and (b) when a field V/x is applied. The electric field displaces charge, causing the material to acquire a dipole moment.

The polarisation of the material, P, is the volume-average of all the dipole moments it contains:

$$P = \frac{\sum d}{\text{volume}} \tag{15.24}$$

Even in materials that are not ionic, like silicon, a field produces a dipole moment because the nucleus of each atom is displaced a tiny distance in the direction of the field, and its surrounding electrons are displaced in the opposite direction (Figure 4.22). The resulting dipole moment depends on the magnitude of the displacement and the number of charges per unit volume, and it is this that determines the dielectric constant. The bigger the shift, the bigger the dielectric constant. Thus compounds with ionic bonds, and polymers that contain polar groups like $-OH^-$ and $-NH^-$ (nylon, for example), have larger dielectric constants than those that do not.

Dielectric loss Think now of polarisation in an alternating electric field. When the upper plate of Figure 15.11(b) is negative, the displacements are in the direction shown in the figure. When its polarity is reversed, the negative ions are displaced upwards and the positive ions downwards; in an oscillating field, the ions oscillate. If their oscillations were exactly in phase with the field, no energy would be lost, but this is never exactly true, and often the phase shift is considerable. Materials with high dielectric loss usually contain awkwardly shaped molecules that themselves have a dipole moment — the water molecule is an example (look back at Figure 4.24). These respond to the oscillating field by rotating, but because of their shape they interfere with each other (you could think of it as molecular friction), and this dissipates energy that appears as heat — which is how microwave heating works. As equation (15.17) showed, the energy that is dissipated depends on the frequency of the electric field. Generally speaking, the higher the frequency, the greater the power dissipated, but there are peaks at certain frequencies that are characteristic of the material structure.

Dielectric breakdown In metals, as we have seen, even the smallest field causes electrons to flow. In insulators, they can't because of the band gap. But if at some weak spot, one electron is torn free from its parent atom, the force $E.e$ exerted by the field E accelerates it and thus gives it kinetic energy; it continues to accelerate until it collides with another atom. A sufficiently large field can give the electron so much kinetic energy that in the collision it kicks one or more new electrons out of the atom it hits, creating electron-hole pairs, and they in turn are accelerated and gain energy. The result, sketched in Figure 15.12, is a cascade – an avalanche of charge. It can be sufficiently violent that the associated heating damages the material permanently. It can also be harnessed – avalanche-effect transistors use the effect to provide rapid switching of large currents.

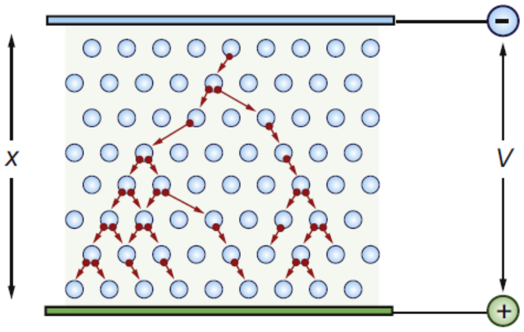

Figure 15.12 Breakdown involves a cascade of electrons like a lightning strike.

The critical field strength to make this happen, called the *breakdown potential*, is hard to calculate; it is that at which the first electron breaks free at the weak spot, a defect in the material such as a tiny crack, void, or inclusion that locally concentrates the field. The necessary fields are large, typically 1–15 MV/m. That sounds like a lot, but such fields are found in two very different circumstances: when the voltage V is very high, or the distance x is very small. In power transmission, the voltages are sufficiently high – 400,000 volts or so – that breakdown can occur at the insulators that support the line, whereas in microcircuits and thin-film devices, the distances between components are quite small: a 1 V difference across a distance of 1 micron gives a field of 1 MV/m.

Piezoelectric materials The word 'Quartz' on the face of your watch carries the assurance that its time-steps are set by the oscillations of a piezoelectric quartz crystal. Piezoelectric behaviour is found in crystals in which the ions are not symmetrically distributed (the crystal structure lacks a centre of symmetry), so that each molecule carries a permanent dipole moment (Figure 15.13(a)). If you cut a little cube from such a material, with faces parallel to crystal planes, the faces would carry charge. This charge attracts ions and charged particles from the atmosphere just as a television screen does, giving an invisible surface layer that neutralises the charge.

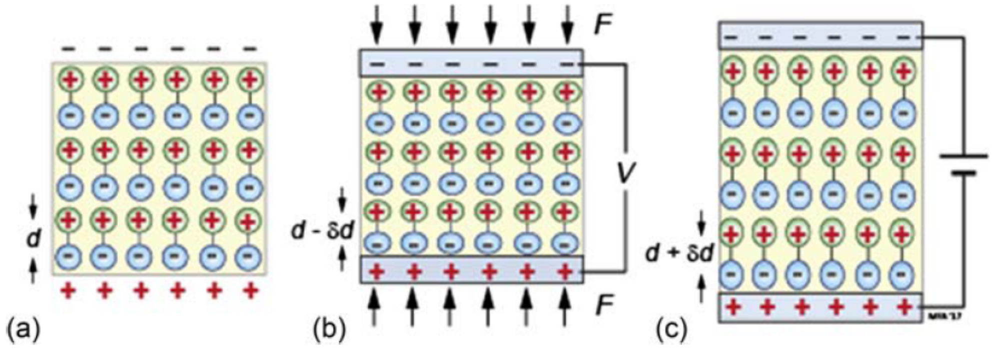

Figure 15.13 (a) A piezoelectric material has a non-symmetrically distributed charge, giving it a natural dipole moment. (b) When deformed, the dipole moment changes and the surfaces become charged. (c) The inverse is also true; a field induces a change of shape, the basis of piezoelectric actuation.

If you now squeeze the crystal, its ions move relative to each other, the dipole moment changes, and the charge on the surface changes too (Figure 15.13(b)). Given time, the newly appeared charge would attract neutralising ions, but this does not happen immediately, giving a potential difference. This provides the basis of operation of electric microphones and pick-ups. The potential difference between the faces can be large – large enough to generate a spark across a narrow gap – and this is the way that gas lighters work.

A strain, then, induces an electric field in a piezoelectric material. The inverse is also true: a field induces a strain. The field pulls the positive ions and pushes the negative ones, changing their spacing and so changing the shape of the crystal (Figure 15.13(c)). If a small strain produces a large field, then a large field will produce only a very small strain. But the strain is a linear function of field, allowing extremely precise, if small, displacements used for positioning and actuation at the sub-micron scale.

Piezoelectric materials respond to a change in electric field faster than most materials respond to a stimulus of this or any other kind. Put them in a megahertz field and they respond with microsecond precision. That opens up many applications, some described later in this chapter. In particular, it opens up the world of ultrasonics – sound waves with frequencies starting at the upper limit of the human ear, 20 kHz, on up to 20,000 kHz and above.

Pyroelectric materials The Greek philosopher Theophrastus[9] noted that certain stones, when warmed or cooled, acquired the ability to pick up straw and dry leaves. It was not until the 20th century that this pyroelectric behaviour – polarisation caused by change of temperature – was understood and exploited.

Some materials have a permanent dipole moment because their positive and negative ions balance electrically but are slightly out of line with each other. If a thin disk of one of these is cut so that its faces are parallel to the plane in which the misalignment happens, the disc has a spontaneous dipole moment P_s of its own. The unit cells of pyroelectric materials are like this.

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[9] Theophrastus (372–287 BC), successor to Aristotle, a teacher of science and author of a ten-volume *History of Plants*, which remained the most important contribution to botanical science for the following 1200 years.

The net dipole moment exists in the absence of an applied electric field and is equivalent to a layer of bound charge on each flat surface (Figure 15.14(a)). Nearby free charges such as electrons or ions are attracted to the surfaces, neutralising the charge. Imagine that conductive electrodes are then attached to the surfaces and connected through an ammeter. If the temperature of the sample is constant, then so is P_s, and no current flows through the circuit. An increase in temperature, however, causes expansion and disorder among the dipoles, changing the net dipole moment and the polarisation. Redistribution of free charges to compensate for the change in bound charge results in a current flow – the pyroelectric current – in the circuit (Figure 15.14(b)). Cooling rather than heating reverses the sign of the current. The pyroelectric current only flows while the temperature is changing; it's the way that intruder alarms, automatic doors, and safety lights are activated.

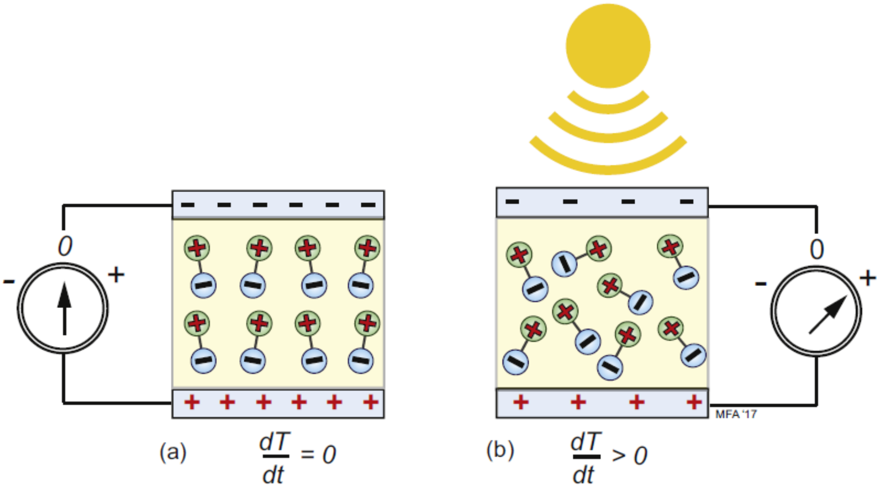

Figure 15.14 Pyroelectric behaviour.

In an open circuit, the free charges remain on the electrodes, which has its uses too, described in the next section. Pyroelectric materials include minerals such as tourmaline (the one Theophrastus found), ceramics such as barium titanate, polymers such as polyvinylidene fluoride, and even biological materials, such as collagen.

Ferroelectric materials Ferroelectrics are a special case of piezoelectric behaviour. They, too, do not have a symmetric structure but have the special ability to switch asymmetry. Barium titanate ($BaTiO_3$), shown schematically in Figure 15.15, is one of these. Below a critical temperature, the Curie[10] temperature (about 120°C for barium titanate), the titanium atom, instead of sitting at the centre of the unit cell, is displaced – either up or down, as in (a) and (b), or to one of the four other equivalent positions round the central position. Above the

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[10] Pierre Curie (1859–1906), French physicist, discoverer of the piezoelectric effect and of magnetic transformations; and husband of the yet more famous Marie Curie. He was killed in a street accident in Paris, a city with dangerous traffic even in 1906.

Curie temperature, the asymmetry disappears and with it the dipole moment, as in (c). In ferroelectrics, these dipoles spontaneously align so that large volumes of the material are polarised even when there is no applied field.

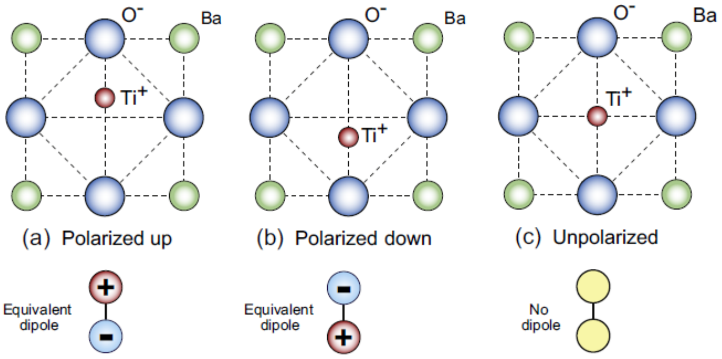

Figure 15.15 Ferroelectric materials have a permanent dipole moment that can switch; here the Ti^+ ion can flip from the upper to the lower position. Above the Curie temperature, the asymmetry disappears.

In the absence of an external field, a ferroelectric divides itself up into *domains* – regions in which all the dipoles are aligned in one direction – separated by *domain walls* at which the direction of polarisation changes (Figure 15.16). The domains orient themselves so that the dipole moment of each domain more or less cancels that of its neighbours. If a field is applied, the domain walls move so that those polarised parallel to the field grow and those polarised across or against it shrink, until the entire sample is polarised (or 'poled') in just one direction.

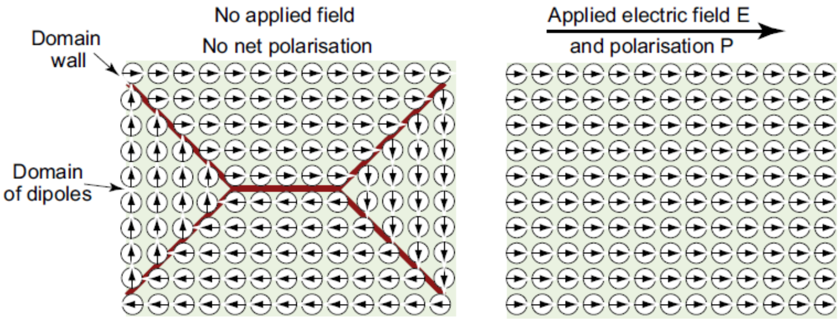

Figure 15.16 Ferroelectric domains arrange themselves so that their dipole moments cancel. In an electric field *E* they align, giving the crystal a net dipole moment, which can be large.

Figure 15.17 shows how the polarisation P changes as the field E is increased: P increases, reaching a maximum at the *saturation polarisation* P_s. If the field is now removed, a large part of the polarisation remains (the *remanent polarisation*), which is only removed by reversing the field to the value $-E_c$, the *coercive field*. The figure shows a complete cycle through full reverse polarisation, ending up again with full forward poling. The little inserts show the domain structures at points around the cycle.

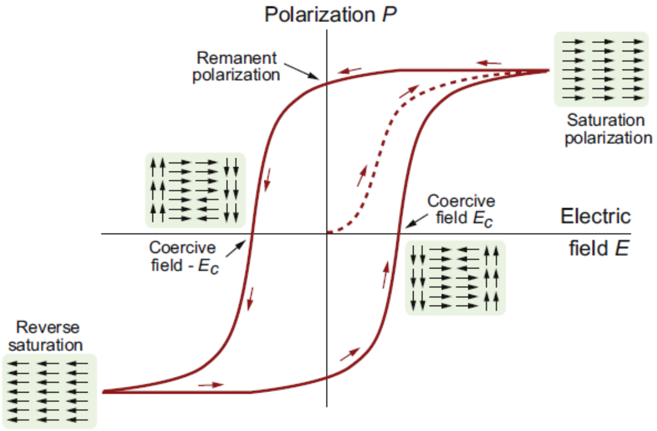

Figure 15.17 A ferroelectric hysteresis curve.

Ferroelectric materials have enormous dielectric constants. Those of normal materials with symmetric charge distributions lie in the range 2–20. Those for ferroelectrics can be as high as 20,000. It is this that allows their use for making super-capacitors that can store 1000 times more energy than conventional capacitors. Such is their energy density that super-capacitors now compete with batteries in kinetic-energy recovery systems for vehicles.

15.6 Summary and conclusions

All materials contain charged particles: electrons, protons, ions, charged molecules, and the like. An electric field E exerts a force qE on a charge q, pushing it in the direction of the field if q is positive and in the opposite direction if q is negative. If the particles can move freely, as electrons can in metals, an electric current flows through the material, which we refer to as conduction. Special types of conduction are also found – superconductivity at very low temperatures, and semiconduction in the materials of electronics such as silicon and germanium. If, instead, the particles cannot move freely, as is the case in insulators, they are still displaced slightly by the field, leading to dielectric polarisation.

Materials that polarise easily have a high dielectric constant. If used as the insulating film of a capacitor, the polarisation screens the electrodes from each other, increasing the capacitance. The slight displacement of charge has other consequences. One of these is electrostriction – the charge movement causes the material to change shape slightly. If the material is made up of ions and these are arranged in a way that lacks a centre of symmetry, a further effect appears, that of piezoelectric response. The lack of symmetry means that each molecule carries a dipole moment, and within a single crystal these are aligned. An electric field causes a change of shape, and a change of shape changes the molecular dipole moment, thus inducing a change in polarisation and generating a field. A change of temperature, too, changes the molecular dipole moment, so materials that are piezoelectric are also pyroelectric. A few materials have a further property, that of molecular asymmetry that can switch direction because ions can occupy one of several equivalent sites in the crystal. These materials are ferroelectric; the molecular dipoles spontaneously align to form polarised domains. In the relaxed state, the domains take up orientations such that the field of one is cancelled by those of its neighbours, but when 'poled' by placing it in an electric field, the domains align, giving a large net polarisation that is retained when the field is removed.

All of these effects have practical utility, examples of which are described in this chapter.