ELECTRONS

Electrons are negatively charged, subatomic, elementary particles. As elementary particles, they represent fundamental units of matter—that is, it is believed that they do not consist of smaller units. Electrons can exist as free particles, controllable by electric and magnetic fields, as in the case of a *cathode ray,* which consists of a stream of electrons. They also represent an important building block of atoms, which are modeled as nuclei surrounded by electrons. Atomic electrons are arranged in certain allowed energy levels and orbitals called *shells.* The chemical properties of an atom are largely determined by the number of electrons in the outer shell, farthest from the nucleus. It is the outer-shell electrons that are principally involved in the bonds holding atoms together in molecules and solids.

FUNDAMENTAL PROPERTIES

The fundamental properties of free electrons include those of (1) charge, (2) mass, and (3) magnetic moment. Franklin (1) describes the experimental and theoretical developments associated with the determination of these properties in the latter part of the nineteenth century and early part of the twentieth century. Discovery of the electron as a physical entity is attributed to Joseph J. Thomson, who in 1897 deduced from experiment that cathode rays consist of "charges of negative electricity carried by particles of matter" (2). In subsequent years, these particles received the nomenclature of *electrons.* Thomson's experimental results produced a value for the electron's charge-to-mass ratio e/m, based on the deflection of cathode rays in magnetic and electrostatic fields. However, his experiments did not produce values for mass and charge separately. Robert Millikan accomplished this in a series of oil drop experiments, begun in 1909, which showed that the electrical charge on the drops was always equal to integer multiples of a specific unit of charge e. He combined his numerical results for e with previous measurements of e/m to obtain values close to the currently accepted values of $e = 1.60217733 \times 10^{-19}$ C and $m = 9.1093897 \times 10^{-31}$ kg for the charge and mass of the electron, respectively (3).

The charge and mass of the electron are directly related to its dynamic behavior since the force, $\boldsymbol{F}$, experienced by a free electron as a result of an electric field, $\boldsymbol{E}$, and a magnetic field, $\boldsymbol{B}$, is given by

$$\boldsymbol{F} = m\boldsymbol{a} = \frac{d\boldsymbol{p}}{dt} = -e\boldsymbol{E} - e(\boldsymbol{v} \times \boldsymbol{B}) \tag{1}$$

where $\boldsymbol{v}$, $\boldsymbol{a}$, and $\boldsymbol{p}$ are the electron's velocity, acceleration, and momentum, respectively. For sufficiently large velocities, the electron's mass increases as predicted by principles of relativity. Equation (1) may be used to account for an electron's classical dynamics in free space when under the influence of electric and magnetic fields. It demonstrates that the trajectory of an electron can be controlled by applied fields, a fact that

is put to use in a wide variety of applications ranging from electron accelerators, to vacuum tubes, to cathode ray tube displays.

Regarding the electron's magnetic moment, Dirac showed in 1928 that a relativistic, quantum-mechanical treatment of the electron indicates an intrinsic angular momentum. Associated with this angular momentum is a magnetic moment equal to $\pm eh/4\pi m$, where h is Planck's constant. The property of intrinsic angular momentum is referred to as *spin* and had been hypothesized earlier by S. A. Goudsmit and G. E. Uhlenbeck. An electron can have either "spinup" or "spindown," depending on the sign of the magnetic moment.

Quantum mechanics also predicts that an electron will have a wavelike nature. That this is true is evidenced in several experiments, including electron diffraction effects in crystals. From the de Broglie relationship between momentum p and wavelength λ (4)

$$p = \frac{h}{\lambda} \tag{2}$$

where h is Planck's constant. For example, a free electron accelerated from rest through a potential of 100 V gains a kinetic energy of 100 eV equal to $p^2/2m$. Solving for p and then using Eq. (2) results in a wavelength of 0.123 nm.

From a broader perspective, electrons belong to the class of elementary particles known as *leptons,* which includes the electron, muon, tau, and three neutrinos. The first three each have one unit of electric charge, e, whereas the neutrinos are neutral. Based on their spin properties, all obey Fermi-Dirac statistics and are referred to as *fermions.* Perl (5) notes that the elementary particles are less than 10^{-16} m in extent and perhaps have no detectable size. However, knowledge of the quantum-mechanical wave function associated with a particular electron allows accurate calculation of the probability of finding it in a particular spatial region.

ATOMIC ELECTRONS

Electrons that exist in atomic orbitals maintain the fundamental properties of charge, mass, and spin described in the preceding section. In addition, they obtain additional attributes as dictated by the laws of quantum mechanics. These additional properties are principally associated with allowed energy and momentum states.

Many of the key properties of atomic electrons can be understood by considering the electron associated with the simplest atom, the hydrogen atom, H. The solution of Schrödinger's equation for the single electron associated with H results in only certain energy eigenvalues and therefore certain allowed electron energies. These energies may be expressed as binding energies according to (4)

$$E_n = \frac{me^4}{8\epsilon_0^2 n^2 h^2} \tag{3}$$

where ϵ_0 is the free-space permittivity and n can have integer values. The largest binding energy is therefore for $n = 1$, for which $E_n = 13.6$ eV. This is the energy required to free an electron from the hydrogen atom when the electron is in the lowest possible state or ground state. The parameter n is referred to as the principal quantum number, or total quantum

number, and also designates the shell number. The electron energies predicted by Eq. (3) are identical to those predicted by Bohr in his 1913 model for the atom.

Three additional quantum numbers result from the Schrödinger equation solution for a hydrogen-atom electron. These are the orbital angular momentum quantum number, l, which determines the magnitude of orbital angular momentum and which can take on positive integer values up to $n - 1$ as well as zero; the magnetic quantum number, m_l, which determines the vector direction of the orbital angular momentum and which can take on integer values ranging from $-l$ to $+l$ as well as zero; and the spin quantum number, which determines either spin up or spin down. The set of four quantum numbers uniquely determines the state of the atomic electron in terms of its energy and momentum.

The Schrödinger equation solution for the hydrogen-atom electron also results in a set of allowed eigenfunctions. These correspond to the electron's quantum-mechanical wave function $\Psi(r, t)$, where r represents the spatial coordinates of the electron and t represents the time variable. The probability of the electron being in an incremental volume dr is $\Psi^*(r, t) \Psi(r, t)dr$. The wave function is useful in calculating the expected value of physical observables. For example, taking $r = 0$ to be at the nucleus, the average distance from the nuclei for an electron is given by

$$\langle r \rangle = \int_0^\infty \Psi^*(r,t) r \Psi(r,t) \, dr \tag{4}$$

where the functional form of Ψ depends on the electron's quantum numbers. The wave-function solutions for atomic electrons are generally fairly complex, involving Legendre functions and Laguerre polynomials (4) and are beyond the scope of this discussion. However, a useful approximation for the average distance of an nth shell electron from the hydrogen nucleus is obtained from the Bohr model as

$$r_n = \frac{\epsilon_0 n^2 h^2}{\pi m e^2} \tag{5}$$

For the innermost shell, that is, $n = 1$, the average distance is calculated from Eq. (5) to be 0.53 Å.

For more complex atoms, with atomic number $Z > 1$, the Bohr approximations represented by Eqs. (3) and (5) are modified by adding Z^2 to the numerator of Eq. (3) and Z to the denominator of Eq. (5). Atoms with more than one electron represent systems of three or more bodies, so closed-form analytical solutions to Schrödinger's equation are not obtained. Perturbation approaches must be applied to obtain solutions. Of principal note, however, is that the four quantum numbers associated with the hydrogen-atom solution still apply to the electrons of more complex atoms. This, combined with the Pauli exclusion principle, provides considerable insight into the nature of atoms.

The Pauli exclusion principle requires that no two electrons in a given system, in this case the atom, have exactly the same set of quantum numbers. Therefore, for the innermost shell with $n = 1$, only two electrons are allowed; the second shell with $n = 2$ can have a maximum of eight electrons; and so on. There is direct correlation between the quantum numbers and conventional chemical notation for shells and subshells. For example, electrons with a principal quantum number of 2 and orbital angular momentum quantum number of 0 correspond to $2s$ electrons using chemistry symbolism. Electrons with a principal quantum number of 3 and an orbital angular momentum quantum number of 1 correspond to $3p$ electrons. For silicon atoms, for example, with 14 total electrons, the order of filling of shells is such that ground-state (or minimum-energy) electron configuration is $1s^2 2s^2 2p^6 3s^2 3p^2$. The first and second shells are entirely filled and there are four electrons in the third shell, which is the outer shell. For carbon atoms with six electrons, the ground-state electron configuration is $1s^2 2s^2 2p^2$. Again there are four electrons in the outer shell, which in this case corresponds to $n = 2$.

Elements with identical outer-shell configurations tend to have similar chemical and physical properties. Consequently, the physical and chemical properties of the elements are periodic functions of their atomic number. The periodic table of the elements is organized to show this periodicity. For example, carbon, silicon, and germanium all have four outer-shell electrons and are all in the same column of the periodic table.

ELECTRONS IN SOLIDS

Kittel (6) notes that the attractive interaction between negatively charged electrons and positively charged nuclei are entirely responsible for the cohesion of solids. Exactly how this interaction takes place depends on the atomic arrangement in the solid and on the chemical constituency of the solid. In some solids, all of the electrons are either directly involved in strong bonds between the atoms or are attached to an atom as inner-shell electrons. In this situation, essentially no electrons are free to move through the solid, and such a material would be an electrical insulator. In other cases, a large number of electrons are essentially free to move throughout the solid. Materials for which this is the case are electrical conductors. The distinction between the resistivity of electrical conductors and insulators is striking. At room temperature, the dc resistivity of high-purity silicon dioxide, for example, can be as high as $1 \times 10^{16} \ \Omega \cdot \text{cm}$ while the value for copper is $1.7 \times 10^{-6} \ \Omega \cdot \text{cm}$. A variation of a factor of over 10^{20} in any material property represents a remarkable range.

Crystal Binding

Many solids of interest are crystalline in nature such that the atoms are arranged on a *lattice,* which is a periodic arrangement of points in space. Of the variety of bonding forces observed in crystals, *ionic bonding, metallic bonding,* and *covalent bonding* account for most of the crystalline solids used in electronic devices. These different types of bonding are briefly described as follows.

Ionic crystals are crystals in which outer-shell electrons are transferred from one atom type to another atom type in such a way that the crystal is made up of positive and negative ions. An example is LiF, in which case the one outer-shell electron for lithium is transferred to the outer shell of fluorine, thereby providing fluorine with a complete outer shell. As a result, the lithium atom has a positive charge and the fluorine atom has a negative charge. Such crystals tend to be electrical insulators. They form relatively close-packed structures such as those associated with the body-centered-cubic and hexagonal-close-packed lattices (6). Compounds involving

an element from column I of the periodic table combined with an element from column VII of the periodic table are good examples of ionic crystals.

Metallic crystals may be envisioned as an array of ions surrounded by a sea of free electrons. The forces holding the solid together arise from an interaction between the positive ion cores and the surrounding free electrons. These electrons can take part in charge transport under the influence of an applied electric field, and the material is a good conductor. Metallic crystals most often are either face-centered-cubic or body-centered-cubic structures.

In covalent-bonded crystals, each atom shares electrons with its neighbors. For example, in a silicon crystal each silicon atom has four nearest neighbors and four outer-shell electrons. These electrons are shared in electron-pair bonds with the electrons in each pair having opposite spins. The electrical resistivity of covalent crystals is often highly temperature dependent since an electron can be thermally excited out of a covalent bond. In such cases, the crystal is referred to as a semiconductor. However, for materials with very strong covalent bonds, the material is insulating even at high temperatures. Covalent materials often form diamond or zincblende crystal structures as these are well suited to the tetrahedral arrangement of covalent bonds. Elements from column IV of the periodic table and compounds from columns III and V or from columns II and VI often form such crystals. In the latter two cases, the bonding is partially covalent and partially ionic.

Energy Bands

In solids, the energies available to electrons tend to fall into bands of permitted energies that are separated by regions of forbidden energies. This is strictly true in crystalline solids and at least approximately the case in noncrystalline solids. The bands may be considered conceptually as originating from the atomic energy levels of the constituent atoms. When atoms are in close proximity, as is the case for a solid, the wave functions of the outer electrons overlap, essentially constituting a single quantum system of electrons common to the crystal. The interaction between neighboring atoms causes the discrete electron energy levels of individual atoms to spread into ranges of energies. As applied to the solid, the Pauli exclusion principle requires that the number of quantum states associated with, say, the 4s atomic state to be 2N, where N is the number of atoms in the crystal. Since N is a very large number, the separate states are so closely spaced in energy that they essentially form a continuum of permitted energies referred to as an *energy band*. Within an energy band, each quantum state has an energy and a momentum associated with it. An electron that occupies that state will take on that energy and that momentum.

Specific information about the energy states available to electrons is key to understanding the behavior of electrons in crystals. This requires a quantum solution in which Schrödinger's equation is applied to the system of electrons in the solid. The electrical potential experienced by an electron in a crystalline solid will be spatially periodic because the atomic environment of the crystal is spatially periodic. Although it is not possible to know this potential exactly, because of the many-bodied nature of the problem, the very fact that it is periodic leads to important conclusions. Most importantly,

when solving Schrödinger's equation for an electron in *any* periodic potential, the result is that the allowed energies do in fact fall into bands of allowed energies separated by regions of forbidden energies. The existence of well-defined energy bands in crystals is therefore a mathematical result of Schrödinger's equation. The concept of energy bands is also useful in many amorphous solids as well, although experiment indicates a lack of a sharp boundary between forbidden and allowed regions of energy.

The probability of a particular allowed energy state at an energy E being occupied may be calculated from the *Fermi–Dirac distribution function,*

$$f(E) = \frac{1}{\exp[(E - E_{\mathrm{F}})/k_{\mathrm{B}}T] - 1} \tag{6}$$

where k_{B} is Boltzmann's constant and T is the temperature expressed in degrees Kelvin. The quantity E_F is referred to as the Fermi energy. From Eq. (6) it is apparent that an allowed state with energy equal to the Fermi energy has a 50% probability of being occupied by an electron. States with energies several $k_{\mathrm{B}}T$ below the Fermi energy have a high probability of being occupied and states located several $k_{\mathrm{B}}T$ above the Fermi energy have a low probability of being occupied.

How the electrons occupy the energy bands leads to a natural classification of solids as metals, insulators, or semiconductors, according to the charge-transport properties. An energy band that is empty of electrons will clearly not contribute to charge transport or electrical conductivity. Less obviously, a completely full energy band also will not contribute to electrical conductivity. If an electron is to be accelerated by an applied electric field, there must be empty states at higher energies available for the electron to move to. This is not the case for a completely full band in which every available state is already occupied. Therefore, only electrons in partly full energy bands contribute to electrical conductivity.

For metals, Fig. 1 shows that the Fermi energy lies within an energy band so that at all temperatures, some states in
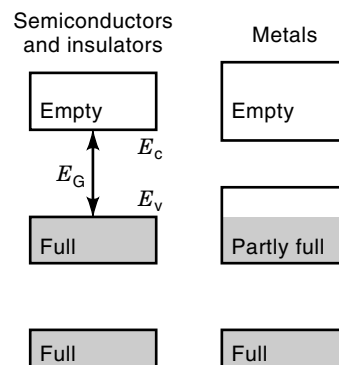

Figure 1. The electron distribution among energy bands in semiconductors and insulators is such that as temperature approaches absolute zero the bands are either completely full or completely empty. Consequently, electrical conductivity vanishes. Semiconductors have smaller energy gaps than insulators and as a result show varying degrees of electrical conductivity as temperature increases. Metals have a partly occupied band at all temperatures and consequently exhibit significant electrical conductivity throughout the temperature range.

the band are occupied and other states are empty. The electrons that are free to respond to an applied electric field are those in this partly full band. The same effect is achieved if there are overlapping bands, providing available empty states. For an insulator, the Fermi energy lies in a forbidden energy region between a band that is essentially full and a band that is essentially empty. This is also illustrated in Fig. 1, which illustrates the *energy gap* E_G as being the extent of the forbidden energy region between the highest full band and lowest empty band. For an insulator the energy gap is several electron-volts, such that even at elevated temperatures the upper band remains essentially empty and the bottom band is full. For a semiconductor the energy gap is smaller such that the Fermi–Dirac distribution results in a nearly full bottom band (the valence band) and a nearly empty top band (the conduction band). The occupancy of these two bands is highly temperature dependent, by nature of the Fermi–Dirac distribution function. Consequently, the electrical conductivity is also highly temperature dependent. Numerical examples of semiconductor energy gaps at room temperature are 0.66 eV for Ge, 1.12 eV for Si, and 1.42 eV for GaAs. In contrast, the energy gap of diamond is approximately 5.5 eV, which is sufficiently high to make diamond, in its pure form, an insulator.

Holes

The missing electrons in the nearly full band of a semiconductor can be treated like positively charged particles, referred to as *holes*. For a sample with unit volume, the current density resulting from a given band can be written as the a sum of ev_α, where v_α is the electron velocity of the αth state and the sum is over all occupied states in the band,

$$J = \sum_\alpha -ev_\alpha \tag{7}$$

Alternatively, J can be written by summing over all the states in the band and then subtracting the contributions of the empty states. This is demonstrated in Eq. (8) in which the sum over β refers to a sum over all allowed states in the band of interest and the sum over γ refers to a summation over the empty states in the band,

$$J = \sum_\beta -ev_j - \sum_\gamma -ev_l \tag{8}$$

However, as previously noted, a full band contributes zero to current flow, so the summation over β in Eq. (8) is equal to zero. For every allowed state with positive velocity there is a state with a corresponding negative velocity. Consequently, Eq. (8) reduces to

$$J = \sum_\gamma +ev_\gamma \tag{9}$$

Therefore the current resulting from electron motion within a particular band may be viewed equivalently as either equal to the sum over all occupied states, ascribing a negative charge to each occupied state, or as the sum over all empty states, ascribing a positive charge to each empty state. The first view corresponds to the physical electrons with charge $-e$ and the second view corresponds to *quasiparticle*

holes with charge $+e$. These quasiparticles provide another way of accounting for the collective behavior of the population of electrons in the band. In principle, the electron flow associated with any energy band can be treated as being due to either electrons or holes. In practice, holes are used to account for charge flow in nearly full bands and electrons are used to account for charge flow in nearly empty bands. In a semiconductor, as previously noted, the nearly full band is referred to as the valence band and the nearly empty band is referred to the conduction band. Electrons in the valence band correspond to those outer-shell electrons that are involved with covalent or ionic bonds. Electrons in the conduction band correspond to electrons that have been liberated from such bonds.

In semiconductors, and to some extent insulators, the electrical conductivity can be altered by shifting the Fermi energy up or down in the energy gap. This is done by adding trace amounts of impurities, a process known as *doping*. Adding an impurity atom that has an extra valence electron, such as adding phosphorus to silicon, moves the Fermi energy closer to the conduction band. The electron concentration in the conduction band is then much larger than the hole concentration in the valence band. The impurity is referred to as a *donor,* because it donates an electron to the conduction band, and the material is referred to as an *n-type* semiconductor. Alternatively, adding an impurity atom that has one less valence electron, such as adding boron to silicon, moves the Fermi energy closer to the valence band. In this case the hole concentration in the valence band is much larger than the electron concentration in the conduction band. This type of impurity is referred to as an *acceptor,* because it accepts an electron from the valence band, and the semiconductor is referred to as *p type*. The electrical conductivity of a crystal can be modified over a large range by adding dopants. For example, when diamond is doped with boron such that boron atoms substitute for carbon atoms, diamond takes on the characteristics of a *p type* semiconductor, and the resistivity can decrease from approximately 10^{15} $\Omega \cdot$cm for pure diamond to less than 1 $\Omega \cdot$ cm even though the doping concentration represents a small atomic percentage. In silicon electronic devices, donor and acceptor concentrations are typically in the parts-per-million range.

E(k) Plots

An informative view of energy bands is via E versus $\boldsymbol{k}$ plots, where $\boldsymbol{k}$ is a three-dimensional vector related to the electron's momentum. The wave-function solution to Schrödinger's equation for the case of a periodic potential take the form of Bloch functions, which extend throughout the crystal and are written as

$$\Psi(\boldsymbol{r}, t) = u_{n,k}(\boldsymbol{r}) \exp[-j(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t)] \tag{10}$$

where $u_{n,k}(\boldsymbol{r})$ represents the periodicity of the lattice, n refers to a specific band, and ω is related to the electron's energy. Equation (10) shows that $\boldsymbol{k}$ is the wave vector associated with the electron's quantum mechanical wave function. It also plays an integral role in the electron's dynamics and it may be shown (7) that

$$\frac{h}{2\pi}\frac{d\boldsymbol{k}}{dt} = -e\boldsymbol{E} - e(\boldsymbol{v} \times \boldsymbol{B}) \tag{11}$$

Comparing Eq. (1) and Eq. (11) it is seen that $h\boldsymbol{k}/2\pi$ plays the role that momentum does in classical mechanics. The quantity $\boldsymbol{k}$ is referred to as the crystal momentum and, along with n, defines an electron's quantum state. In a crystal, the state of an electron may be considered to be defined by the four quantum numbers n, k_x, k_y, and k_z, where the latter three are the vector components of $\boldsymbol{k}$.

Figure 2 illustrates the two main types of $E(\boldsymbol{k})$ plots for semiconductors, *direct-gap* materials and *indirect-gap* materials. Direct-gap materials are characterized by a conduction-band minimum E_C, which is directly above the valence-band maximum E_V, in $\boldsymbol{k}$ space, usually at $\boldsymbol{k} = \boldsymbol{0}$. Indirect-gap materials have an offset in $\boldsymbol{k}$ space between E_C and E_V. The distinction is important in terms of transitions of electrons from one band to another. Such transitions must conserve both energy and momentum. For a direct-gap material, a transition between states near E_C and E_V does not involve an appreciable change in $\boldsymbol{k}$ or momentum. Energy can be conserved on a downward transition by emission of a photon of energy $E_C - E_V$, or on an upward transition by absorption of a photon, since photon momentum is small. Direct-gap semiconductors are generally effective light emitters. Examples are GaAs and GaP, which are used for light-emitting diodes and solid-state lasers. For indirect-gap semiconductors, however, photon emission would not alone be sufficient to conserve both energy and momentum. Such materials are generally not effective light emitters, and examples are Si and Ge.

Effective Mass

When an electric field or magnetic field is applied to a crystal, the electrons experience not only the forces due to the applied field but also the internal forces in the crystal due to nuclei and other electrons. The rather surprisingly simple net result of this complex situation is that the electron moves in response to the applied field as if it had a mass different than the actual gravitational mass of a free electron. The motion of the electron in the combined periodic and external fields is as if it were moving in response to the external field only, but with *an effective mass m**. The effective mass can be larger or smaller than the actual gravitational electron mass m and can even be negative.

When E is an isotropic function of k, the effective mass is related to d^2E/dk^2 as

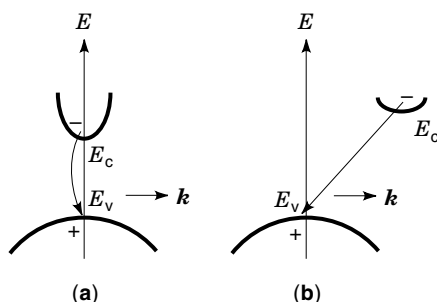$$m^* = \frac{h^2}{4\pi^2(d^2E/dk^2)} \tag{12}$$

Figure 2. Band-to-band transitions in direct-gap semiconductors (a) can take place without significant changes in the crystal momentum k. Indirect-gap semiconductors (b) have band edges of the conduction band and valence band that are widely separated in k space.

For many semiconductors, the energy is a parabolic function of k, or nearly a parabolic function, such that m^* is approximately constant. For example, the electrons located near the bottom of the conduction band in GaAs have an effective mass equal to $0.068m$. If the dimensions of the crystal are large compared to atomic dimensions, the dynamic behavior of conduction-band electrons in response to applied fields is determined from Eq. (1), with m replaced by m^*. Electrons with a small effective mass have a high *mobility,* which is the average drift velocity per unit electric field.

More generally, when E is an anisotropic function of k, the effective mass is a tensor for which the components are given by

$$\left(\frac{1}{m^*}\right)_{ij} = \frac{4\pi^2}{h^2}\frac{\partial^2 E}{\partial k_i \partial k_j} \tag{13}$$

When the effective mass is in the form of a tensor, the direction of the acceleration vector is not necessarily in the direction of the force vector.

The curvature of energy bands in k space is such that some states have a negative effective mass. Kittel (6) notes that the phenomena of negative effective mass is associated with the Bragg reflection of the electrons for which, in going from a state k to a state with $k + \Delta k$, the momentum transfer from the crystal to the electron is opposite to and larger than the transfer of momentum from the external field to the electron. As a result there is an overall decrease in the forward momentum of the electron and the effective mass is negative. The dynamic behavior of valence-band holes in response to applied fields may also be described by an effective mass.

CURRENT DEVELOPMENTS

After over 100 years of study, the electron may be considered to be among the best understood of the elementary particles. However, there are still new developments taking place both on theoretical and application fronts. Of particular theoretical interest are systems that exhibit apparent fractionalization of electrons. Under certain circumstances, experimental observations of electronic phenomena in solids appear to indicate particles that behave as though an electron has broken into pieces containing, for example, one-third or one-fifth of its charge, or into separate particles, one containing an electron's charge and another containing its spin. Anderson (8) notes that such behavior may be interpreted from a quasiparticle perspective rather than a physical disintegration of an electron. Although there is nothing present but physical electrons with the usual charge and spin, the composite behavior is explainable by quantum particles with fractional charge. The situation is reminiscent of conductivity associated with semiconductor valence bands, in which the behavior of the entire population of electrons is explainable in terms of the quasiparticle holes. The quantum nature of the electron is also inherent to the development of new electron device structures in which the dimensions are measured in nanometers. The layers in such devices may be only a few atomic layers thick and represent artificially made quantum structures, the dimensions of which are on the order of the wavelength of the electron and which are designed for particular device functions such as switching. Such structures have exhibited elec-

trical operation in the terahertz frequency range (9). Also included in this general area are quantum-dot-type devices, which may be useful in information storage.

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ELECTRON SOURCE.   See CATHODES.
ELECTRON WIND EFFECT.   See ELECTROMIGRATION.