Figure 1.2 Energy bandgap versus lattice constant for common elemental and compound semiconductors. The tie lines joining the binaries represent ternary compositions. The dashed lines represent indirect bandgap material. The vertical dashed line passing through the point representing InP contains the bandgaps for the lattice-matched InGaAlAs and InGaAsP quaternary systems.

emission energies for light sources. However, by alloying it is possible to vary the bandgap *continuously* and monotonically, and together with it the bandstructure, electronic, and optical properties. The formation of ternary and quaternary compounds of varying bandgaps also enables the formation of heterojunctions, which have become essential for the design of high-performance electronic and optoelectronic devices. As an example, the bandgap of the ternary compound $Al_xGa_{1-x}As$ ($0 \leq x \leq 1$) depends on the mole fraction x of AlAs in the solid solution and changes continuously from 1.43 eV (GaAs, $x = 0$) to 2.1 eV (AlAs, $x = 1$). As we shall see later, the bandstructure, electronic, and optical properties of the mixed crystal also change with change in alloy composition, and these are exploited in the design of electronic and optoelectronic devices. Among the common GaAs and InP-based ternary and quaternary compounds, the properties of $Al_xGa_{1-x}As$ have been most thoroughly investigated. Other important ternary and quaternary compounds are $GaAs_{1-x}P_x$, $In_{1-x}Ga_xP$, $In_xGa_xAl_{1-x-y}As$, and $In_{1-x}Ga_xAs_yP_{1-y}$. The last two are usually grown on InP substrates. The bandgaps and lattice constants of these compounds can be found from the tie lines in Fig. 1.2. The quaternary compounds mentioned above have emerged as being extremely important for optical communication, since their bandgaps correspond to the spectral window in which silica fibers have their lowest loss and dispersion. Several important observations may be made from Fig. 1.2. First, it may be noted that the lattice constants of GaAs (5.6532 Å) and AlAs (5.6611 Å) are almost identical. This implies that all the mixed crystal compositions of $Al_xGa_{1-x}As$ can be grown *lattice-matched* on GaAs substrates. We shall soon see in Sec. 1.5 that this is very useful because any thickness

of the ternary crystal can be grown without having to wo generation of dislocations. Similarly certain mixed crystal

nary alloys InGaAlAs and InGaAsP are lattice-matched to end-point compositions $In_{0.53}Ga_{0.47}As$ ($\mathcal{E}_g = 0.74$ eV) to In and $In_{0.53}Ga_{0.47}As$ to InP (1.35 eV), respectively, for the tw that the only ternary $In_xGa_{1-x}As$ composition lattice-mat All other compositions from $x = 0$ (GaAs) to $x = 1$ (InAs) w match between these two end-point binaries is 7%. Th Fig. 1.2 is that certain compositions of the ternary a depending on the nature of the binary constituents, have i indicated by dashed tie lines. For example, $Al_xGa_{1-x}As$ 0.43 and AlAs is, of course, an indirect bandgap semic noted that these mixed crystals are formed by mixing in th group V sublattice, or both. This point has an important be to grow them.

Many physical parameters of ternary compounds are ters of the constituent binaries and vary roughly linearly w ple, the lattice constant, a, of $In_xGa_{1-x}As$ is given by Veg

$$a_{In_xGa_{1-x}As} = x a_{InAs} + (1-x) a_{Ga}$$

Similarly, for a quaternary compound $Al_{1-x}B_xC_yD_{1-y}$, a expressed as

$$Q(x,y) = \{x(1-x)[(1-y)[(1-x)T_{12}(x) +$$
$$+ y(1-y)[(1-x)]T_{14}(y)$$
$$[x(1-x)+y(1-y)]^{-1}$$

where T_{ij} is the material parameter for the ternary alloy f relevant parameters of GaAs and $In_{0.53}Ga_{0.47}As$ togeth pose of comparison, are listed in Appendix 1.

1.2 BONDING IN SOLIDS

In the *solid state*, also referred to as *condensed matter*, th held together by bonding forces. The atoms also mainta each other. If the array of atoms have long-range orde solid is crystalline, and we will study the properties of c periodic array of atoms leads the way to the energy ban erties. However, before going into all that, we should forces that hold the atoms together ir their equilibrium two types of forces, attractive and repulsive, which are b ic distance z. At large distances the attractive forces don are drawn nearer to each other. At small interatomic dominate, and the atoms are pushed further apart. In e tion $F_A(z)$, and repulsion, $F_R(z)$, must balance to establis ing. In other words: