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This chapter reviews the principles of band-gap engineering and quantum confinement in semiconductors, with a particular emphasis on their optoelectronic properties. The chapter begins with a review of the fundamental principles of band-gap engineering and quantum confinement. It then describes the optical and electronic properties of semiconductor quantum wells and superlattices at a tutorial level, before describing the principal optoelectronic devices. The topics covered include edge-emitting lasers and light-emitting diodes (LEDs), resonant cavity LEDs and vertical-cavity surface-emitting lasers (VCSELs), quantum cascade lasers, quantum-well solar cells, superlattice avalanche photodiodes, inter-sub-band detectors, and quantum-well light modulators. The chapter concludes with a brief review of current research topics, including a discussion of quantum-dot structures.

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them. In Sects. 42.3–42.5 we will explain the principles of the main optoelectronic devices that employ quantum wells and superlattices, namely emitters, detectors and modulators. Finally we will indicate a few interesting recent developments that offer exciting prospects for future devices before drawing the chapter to its conclusion. A number of texts cover these topics in more detail (e.g. [42.2–5]), and the interested reader is referred to these sources for a more comprehensive treatment. A description of the purely electronic properties of low-dimensional structures may be found in [42.6].

42.1 Principles of Band-Gap Engineering and Quantum Confinement

42.1.1 Lattice Matching

The art of band-gap engineering relies heavily on developments in the science of crystal growth. Bulk crystals grown from the melt usually contain a large number of impurities and defects, and optoelectronic devices are therefore grown by epitaxial methods such as liquid-phase epitaxy (LPE), molecular-beam epitaxy (MBE) and metalorganic vapour-phase epitaxy (MOVPE), which is also called metalorganic chemical vapour deposition (MOCVD) (Chapt. 14). The basic principle of epitaxy is to grow thin layers of very high purity on top of a bulk crystal called the substrate. The system is said to be lattice-matched when the lattice constants of the epitaxial layer and the substrate are identical. Lattice-matching reduces the number of dislocations in the epitaxial layer, but it also imposes tight restrictions on the band gaps that can be engineered easily, because there are only a relatively small number of convenient substrate materials available.

![Fig. 42.1](image)

**Fig. 42.1** Room-temperature band gap of a number of important optoelectronic III–V materials versus their lattice constant.

We can understand this point more clearly by reference to Fig. 42.1. This diagram plots the band-gap energy $E_g$ of a number of important III–V semiconductors as a function of their lattice constant. The majority of optoelectronic devices for the red/near-infrared spectral regions are either grown on GaAs or InP substrates. The simplest case to consider is an epitaxial layer of GaAs grown on a GaAs substrate, which gives an emission wavelength of 873 nm (1.42 eV). This wavelength is perfectly acceptable for applications involving short-range transmission down optical fibres. However, for long distances we require emission at 1.3 µm or 1.55 µm, while for many other applications we require emission in the visible spectral region.

Let us first consider the preferred fibre-optic wavelengths of 1.3 µm and 1.55 µm. There are no binary semiconductors with band gaps at these wavelengths, and so we have to use alloys to tune the band gap by varying the composition (Chapt. 31). A typical example is the ternary alloy Ga$_x$In$_{1-x}$As, which is lattice-matched to InP when $x = 47\%$, giving a band gap of 0.75 eV (1.65 µm). Ga$_{0.47}$In$_{0.53}$As photodiodes grown on InP substrates make excellent detectors for 1.55-µm radiation, but to make an emitter at this wavelength, we have to increase the band gap while maintaining the lattice-matching condition. This is achieved by incorporating a fourth element into the alloy — typically Al or P, which gives an extra design parameter that permits band-gap tuning while maintaining lattice-matching. Thus the quaternary alloys Ga$_{0.27}$In$_{0.73}$As$_{0.55}$P$_{0.42}$ and Ga$_{0.40}$In$_{0.60}$As$_{0.85}$P$_{0.18}$ give emission at 1.3 µm and 1.55 µm, respectively, and are both lattice-matched to InP substrates.

Turning now to the visible spectral region, it is a convenient coincidence that the lattice constants of GaAs and AlAs are almost identical. This means that we can grow relatively thick layers of Al$_x$Ga$_{1-x}$As on GaAs substrates without introducing dislocations and other defects. The band gap of Al$_x$Ga$_{1-x}$As varies quadratically
with $x$ according to:

$$E_g(x) = (1.42 + 1.087x + 0.438x^2) \text{eV}, \quad (42.1)$$

but unfortunately the gap becomes indirect for $x > 43\%$. We can therefore engineer direct band gaps of 1.42–1.97 eV, giving emission from 873 nm in the near infrared to 630 nm in the red spectral range. Much work has been done on quaternary alloys such as AlGaInP, (Chapt. 31) but it has not been possible to make blue- and green-emitting devices based on GaAs substrates to date, due to the tendency for arsenic and phosphorous compounds to become indirect as the band gap increases.

The approach for the blue end of the spectrum preferred at present is to use nitride-based compounds. (Chapt. 32) Early work on nitrides established that their large direct gaps made them highly promising candidates for use as blue/green emitters [42.7]. However, it was not until the 1990s that this potential was fully realised. The rapid progress followed two key developments, namely the activation of $p$-type dopants and the successful growth of strained In$_x$Ga$_{1-x}$N quantum wells which did not satisfy the lattice-matching condition [42.8]. The second point goes against the conventional wisdom of band-gap engineering and highlights the extra degrees of freedom afforded by quantum-confined structures, as will now be discussed.

### 42.1.2 Quantum-Confined Structures

A quantum-confined structure is one in which the motion of the electrons (and/or holes) are confined in one or more directions by potential barriers. The general scheme for classifying quantum-confined structures is given in Table 42.1. In this chapter we will be concerned primarily with quantum wells, although we will briefly refer to quantum wires and quantum dots in Sect. 42.6. Quantum size effects become important when the thickness of the layer becomes comparable with the de Broglie wavelength of the electrons or holes.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Confined directions</th>
<th>Free directions (dimensionality)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum well</td>
<td>1 (z)</td>
<td>2 (x, y)</td>
</tr>
<tr>
<td>Quantum wire</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Quantum dot (or box)</td>
<td>3</td>
<td>none</td>
</tr>
</tbody>
</table>

Table 42.1 Classification of quantum-confined structures. In the case of quantum wells, the confinement direction is usually taken as the $z$-axis

If we consider the free thermal motion of a particle of mass $m$ in the $z$-direction, the de Broglie wavelength at a temperature $T$ is given by

$$\lambda_{\text{deB}} = \frac{\hbar}{\sqrt{mk_B T}}. \quad (42.2)$$

For an electron in GaAs with an effective mass of 0.067$m_0$, we find $\lambda_{\text{deB}} = 42$ nm at 300 K. This implies that we need structures of thickness $\approx 10$ nm in order to observe quantum-confinement effects at room temperature. Layers of this thickness are routinely grown by the MBE or MOVPE techniques described in Chpt. 14.

Figure 42.2 shows a schematic diagram of a GaAs/AlGaAs quantum well. The quantum confinement is provided by the discontinuity in the band gap at the interfaces, which leads to a spatial variation of the conduction and valence bands, as shown in the lower half of the figure. The Al concentration is typically chosen to be around 30%, which gives a band-gap discontinuity of 0.36 eV according to (42.1). This splits roughly 2 : 1 between the conduction and valence bands, so that electrons see a confining barrier of 0.24 eV and the holes see 0.12 eV.

If the GaAs layers are thin enough, according to the criterion given above, the motion of the electrons and holes will be quantised in the growth ($z$) direction, giving

![Fig. 42.2 Schematic diagram of the growth layers and resulting band diagram for a GaAs/AlGaAs quantum well of thickness $d$. The quantised levels in the quantum well are indicated by the dashed lines. Note that in real structures a GaAs buffer layer is usually grown immediately above the GaAs substrate](image-url)
rise to a series of discrete energy levels, as indicated by
the dashed lines inside the quantum well in Fig. 42.2.
The motion is in the other two directions (i.e. the x–y
plane) is still free, and so we have quasi two-dimensional
(2-D) behaviour.

The quantisation of the motion in the z-direction
has three main consequences. Firstly, the quantisation
energy shifts the effective band edge to higher energy,
which provides an extra degree of freedom in the art of
band-gap engineering. Secondly, the confinement keeps
the electrons and holes closer together and hence in-
creases the radiative recombination probability. Finally,
the density of states becomes independent of energy,
in contrast to three-dimensional (3-D) materials, where
the density of states is proportional to \( E^{1/2} \). Many of
the useful properties of the quantum wells follow from
these three properties.

The arrangement of the bands shown in Fig. 42.2
in which both the electrons and holes are confined
in the quantum well is called type I band alignment.
Other types of band alignments are possible in which
only one of the carrier types are confined (type II
band alignment). Furthermore, the flexibility of the
MBE and MOVPE growth techniques easily allows the
growth of superlattice (SL) structures containing many
repeated quantum wells with thin barriers separating
them, as shown in Fig. 42.3. Superlattices behave like
artificial one-dimensional periodic crystals, in which
the periodicity is designed into the structure by the
repetition of the quantum wells. The electronic states
of SLs form delocalised minibands as the wave func-
tions in neighbouring wells couple together through
the thin barrier that separates them. Structures con-
taining a smaller number of repeated wells or with
thick barriers that prevent coupling between adjacent
wells are simply called multiple quantum well (MQW)
structures.

42.2 Optoelectronic Properties of Quantum-Confined Structures

42.2.1 Electronic States in Quantum Wells

and Superlattices

Quantum Wells

The electronic states of quantum wells can be understood
by solving the Schrödinger equation for the electrons
and holes in the potential wells created by the band dis-
continuities. The simplest approach is the infinite-well
model shown in Fig. 42.4a. The Schrödinger equation in
the well is

\[
-\frac{\hbar^2}{2m^*_w} \frac{d^2 \psi(z)}{dz^2} = E \psi(z),
\]

where \( m^*_w \) is the effective mass in the well and \( z \) is the
growth direction. Since the potential barriers are infinite,
there can be no penetration into the barriers, and we must
therefore have \( \psi(z) = 0 \) at the interfaces. If we choose
our origin such that the quantum well runs from \( z = 0 \)
Equation (42.5) shows us that the energy is inversely proportional to the effective mass, 

\[ E_n = \frac{\hbar^2 k_n^2}{2m_w^\ast} = \frac{\hbar^2}{2m_w^\ast} \left( \frac{n\pi}{d} \right)^2 \].

The wave functions of the \( n = 1 \) and \( n = 2 \) levels are sketched in Fig. 42.4a.

Although the infinite-well model is very simplified, it nonetheless provides a good starting point for understanding the general effects of quantum confinement. Equation (42.5) shows us that the energy is inversely proportional to \( d^2 \), implying that narrow wells have larger confinement energies. Furthermore, the confinement energy is inversely proportional to the effective mass, which means that lighter particles experience larger effects. This also means that the heavy- and light-hole states have different energies, in contrast to bulk semiconductors in which the two types of hole states are degenerate at the top of the valence band.

Now let us consider the more realistic finite-well model shown in Fig. 42.4b. The Schrödinger equation in the well is unchanged, but in the barrier regions we now have:

\[ -\frac{\hbar^2}{2m_b^\ast} \frac{d^2 \psi(z)}{dz^2} + V_0 \psi(z) = E \psi(z) \],

where \( V_0 \) is the potential barrier and \( m_b^\ast \) is the effective mass in the barrier. The boundary conditions require that the wave function and particle flux \( (1/m^*) d\psi/dz \) must be continuous at the interface. This gives a series of even and odd parity solutions which satisfy

\[ \tan(kd/2) = \frac{m_b^\ast}{m_w^\ast} k \],

and

\[ \tan(kd/2) = -\frac{m_b^\ast}{m_w^\ast} k \],

respectively. \( k \) is the wave vector in the well, given by

\[ \frac{\hbar^2 k^2}{2m_w^\ast} = E_n \].

while \( \kappa \) is the exponential decay constant in the barrier, given by

\[ \frac{\hbar^2 \kappa^2}{2m_b^\ast} = V_0 - E_n \].

Solutions to (42.7) and (42.8) are easily found by simple numerical techniques [42.9]. As with the infinite well, the eigenstates are labelled by the quantum number \( n \) and have parities of \((-1)^{n+1}\) with respect to the axis of symmetry about the centre of the well. The wave functions are approximately sinusoidal inside the well, but decay exponentially in the barriers, as illustrated in Fig. 42.4b. The eigen-energies are smaller than those of the infinite well due to the penetration of the barriers, which means that the wave functions are less well confined. There is only a limited number of solutions, but there is always at least one, no matter how small \( V_0 \) might be.

As an example we consider a typical GaAs/Al\(_{0.3}\)Ga\(_{0.7}\)As quantum well with \( d = 10 \) nm. The confinement energy is 245 meV for the electrons and 125 meV for the holes. The infinite well model predicts \( E_1 = 56 \) meV and \( E_2 = 224 \) meV for the electrons, whereas (42.7), (42.8) give \( E_1 = 30 \) meV and \( E_2 = 113 \) meV. For the heavy (light) holes the infinite-well model predicts 11 meV (40 meV) and 44 meV (160 meV) for the first two bound states, instead of the more accurate values of 7 meV (21 meV) and 29 meV (78 meV) calculated from the finite-well model. Note that the separation of the electron levels is greater than \( k_B T \) at 300 K, so that the quantisation effects will be readily observable at room temperature.

**Strained Quantum Wells**

Even more degrees of freedom for tailoring the electronic states can be achieved by epitaxially stacking semiconductor layers with different lattice constants to form **strained quantum wells**. Examples include...
InGa1–xAs on GaAs, and Si1–xGex on Si. Large biaxial strain develops within the x–y plane of a quantum well grown on a substrate with a different lattice constant. In order to avoid the buildup of misfit dislocations at the interfaces, the strained layers need to be thinner than a certain critical dimension. For example, a defect-free strained InGa1–xAs layer on GaAs requires a thickness less than around 10 nm when x = 0.2. Since the band gap is related to the lattice constant, the strain induces a shift of the band edges which, in turn, affects many other properties. It is due to some of these effects that strained QW structures have become widely exploited in optoelectronic devices. (Chapt. 37)

There are essentially two types of strain. Compressive strain occurs when the active layer has a larger lattice constant than the substrate, for example in InGa1–xAs on GaAs. In this case, the band gap increases and the effective mass of the highest hole band decreases, while that of next valence band increases. The opposite case is that of tensile strain, which occurs when the active layer has a smaller lattice constant than the substrate, such as Si1–xGex on Si. The ordering of the valence bands is opposite to the case of compressive strain, and the overall band gap is reduced.

Superlattices
The analytical derivation of the allowed energy values in a superlattice (SL) is similar to that for a single QW, with the appropriate change of the boundary conditions imposed by the SL periodicity. The mathematical description of a superlattice is similar to a one-dimensional crystal lattice, which allows us to borrow the formalism of the band theory of solids, including the well-known Kronig–Penney model [42.9]. Within this model, the electron envelope wave function ψ(z) can be expressed as a superposition of Bloch waves propagating along the z-axis. For a SL with a barrier height V0, the allowed energy is calculated numerically as a solution of the transcendental equation involving the Bloch wave vector:

\[ \cos(ka) = \cos(kd) \cos(k'b) - \frac{k^2 + \kappa'^2}{2ka'} \sin(kd) \sin(k'b), \]

\[ E > V_0, \]

\[ (42.11) \]

The optical transitions in quantum wells take place between electronic states that are confined in the z-direction but free in the x–y plane. The transition rate can be calculated from Fermi’s golden rule, which states that the probability for optical transitions from the initial state |i⟩ at energy Ei to the final state |f⟩ at energy Ef is given by:

\[ W(i \rightarrow f) = \frac{2\pi}{h} |\langle f | \mathbf{r} \cdot \mathbf{E}(f) | i \rangle|^2 g(\hbar\omega), \]

\[ (42.14) \]

where \( \mathbf{r} \) is the electric dipole of the electron, \( \mathbf{E} \) is the electric field of the light wave, and \( g(\hbar\omega) \) is the joint density of states at photon energy \( \hbar\omega \). Conservation of
energy requires that \( E_f = (E_i + \hbar \omega) \) for absorption, and \( E_f = (E_i - \hbar \omega) \) for emission.

Let us consider a transition from a confined hole state in the valence band with quantum number \( n \) to a confined electron state in the conduction band with quantum number \( n' \). We apply Bloch’s theorem to write the wave functions in the following form:

\[
|i\rangle = u_s(r) \exp(ik_{xy} \cdot r_x) \psi_{nz}(z)
\]

\[
|f\rangle = u_c(r) \exp(ik_{xy} \cdot r_x) \psi_{nz}(z),
\]

where \( u_s(r) \) and \( u_c(r) \) are the envelope function for the valence and conduction bands, respectively, \( k_{xy} \) is the in-plane wave vector for the free motion in the \( x-y \) plane, \( r_x \) being the \( xy \) component of the position vector, and \( \psi_{nz}(z) \) and \( \psi_{nz}(z) \) are the wave functions for the confined hole and electron states in the \( z \)-direction. We have applied conservation of momentum here so that the in-plane wave vectors of the electron and hole are the same.

On inserting these wave functions into (42.14) we find that the transition rate is proportional to both the square of the overlap of the wave functions and the joint density of states [42.11]:

\[
W \propto |\langle \psi_{nz}(z) | \psi_{nz}(z) \rangle|^2 g(\hbar \omega). \tag{42.16}
\]

The wave functions of infinite wells are orthogonal unless \( n = n' \), which gives a selection rule of \( \Delta n = 0 \). For finite wells, the \( \Delta n = 0 \) selection rule is only approximately obeyed, although transitions between states of different parity (i.e., \( \Delta n \) odd) are strictly forbidden. The joint density of states is independent of energy due to the quasi-2-D nature of the quantum well.

Figure 42.5a illustrates the first two strong transitions in a typical quantum well. These are the \( \Delta n = 0 \) transitions between the first and second hole and electron levels. The threshold energy for these transitions is equal to \( \hbar \omega = E_g + E_{hv} + E_{ee} \). \tag{42.17}

The lowest value is thus equal to \((E_g + E_{hv} + E_{ee})\), which shows that the optical band gap is shifted by the sum of the electron and hole confinement energies. Once the photon energy exceeds the threshold set by (42.17), a continuous band of absorption occurs with the absorption coefficient independent of energy due to the constant 2-D density of states of the quantum well. The difference between the absorption of an ideal quantum well with infinite barriers and the equivalent bulk semiconductor is illustrated in Fig. 42.5b. In the quantum well we find a series of steps with constant absorption coefficients, whereas in the bulk the absorption varies as \((\hbar \omega - E_f)^{1/2}\) for \( \hbar \omega > E_f \). Thus the transition from 3-D to 2-D alters the shape of the absorption curve, and also causes an effective shift in the band gap by \((E_{e1} + E_{h1})\).

Up to this point, we have neglected the Coulomb interaction between the electrons and holes which are involved in the transition. This attraction leads to the formation of bound electron–hole pairs called excitons. The excitation states of a quantum well can be modelled as 2-D hydrogen atoms in a material with relative dielectric constant \( \varepsilon_r \). In this case, the binding energy \( E^X \) is given by [42.12]:

\[
E^X(v) = \frac{\mu}{m_0 \varepsilon_r} \frac{1}{(v - 1/2)^2} R_H, \tag{42.18}
\]

where \( v \) is an integer \( \geq 1 \), \( m_0 \) is the electron mass, \( \mu \) is the reduced mass of the electron–hole pair, and \( R_H \) is the Rydberg constant for hydrogen (13.6 eV). This contrasts with the standard formula for 3-D semiconductors in which \( E^X \) varies as \( 1/v^2 \) rather than \( 1/(v - 1/2)^2 \), and implies that the binding energy of the ground-state exciton is four times larger in 2-D than 3-D. This allows excitonic effects to be observed at room temperature in quantum wells, whereas they are only usually observed at low temperatures in bulk semiconductors.

Figure 42.6 compares the band-edge absorption of a GaAs MQW sample with that of bulk GaAs at room temperature [42.13]. The MQW sample contained 77 GaAs quantum wells of thickness 10 nm with thick Al\(_{0.28}\)Ga\(_{0.72}\)As barriers separating them. The shift of
the band edge of the MQW to higher energy is clearly observed, together with the series of steps due to each $\Delta n = 0$ transition. The sharp lines are due to excitons, which occur at energies given by

$$E_X = E_g + E_{hh1} + E_{e1} - E_x.$$  \hspace{1cm} (42.19)

Equation (42.18) predicts that $E_X$ should be around 17 meV for the ground-state exciton of an ideal GaAs quantum well, compared to 4.2 meV for the bulk. The actual MQW exciton binding energies are somewhat smaller due to the tunnelling of the electrons and holes into the barriers, with typical values of around 10 meV. However, this is still substantially larger than the bulk value and explains why the exciton lines are so much better resolved for the MQW than the bulk. The absorption spectrum of the MQW above the exciton lines is approximately flat due to the constant density of states in 2-D, which contrasts with the rising absorption of the bulk due to the parabolic 3-D density of states. Separate transitions are observed for the heavy and light holes. This follows from their different effective masses, and can also be viewed as a consequence of the lower symmetry of the MQW compared to the bulk.

**Emission**

Emissive transitions occur when electrons excited in the conduction band drop down to the valence band and recombine with holes. The optical intensity $I(h\omega)$ is proportional to the transition rate given by (42.14) multiplied by the probability that the initial state is occupied and the final state is empty:

$$I(h\omega) \propto W(c \rightarrow v) f_c(1 - f_v),$$  \hspace{1cm} (42.20)

where $f_c$ and $f_v$ are the Fermi–Dirac distribution functions in the conduction and valence bands, respectively. In thermal equilibrium, the occupancy of the states is largest at the bottom of the bands and decays exponentially at higher energies. Hence the luminescence spectrum of a typical GaAs MQW at room temperature usually consists of a peak of width $\sim k_B T$ at the effective band gap of $(E_g + E_{hh1} + E_{e1})$. At lower temperatures the spectral width is affected by inhomogeneous broadening due to unavoidable fluctuations in the well thickness. Furthermore, in quantum wells employing alloy semiconductors, the microscopic fluctuations in the composition can lead to additional inhomogeneous broadening. This is particularly true of InGaN/GaN quantum wells, where indium compositional fluctuations produce substantial inhomogeneous broadening even at room temperature.

The intensity of the luminescence peak in quantum wells is usually much larger than that of bulk materials because the electron–hole overlap is increased by the confinement. This leads to faster radiative recombination, which then wins out over competing nonradiative decay mechanisms and leads to stronger emission. This enhanced emission intensity is one of the main reasons why quantum wells are now so widely used in diode lasers and light-emitting diodes.

**42.2.3 The Quantum-Confined Stark Effect**

The quantum-confined Stark effect (QCSE) describes the response of the confined electron and hole states in quantum wells to a strong direct-current (DC) electric field applied in the growth ($z$) direction. The field is
usually applied by growing the quantum wells inside a p–n junction, and then applying reverse bias to the diode. The magnitude of the electric field $F$ is given by:

$$F = \frac{V_{\text{built-in}} - V_{\text{bias}}}{L_1},$$ \hspace{1cm} (42.21)

where $V_{\text{built-in}}$ is the built-in voltage of the diode, $V_{\text{bias}}$ is the bias voltage, and $L_1$ is the total thickness of the intrinsic region. $V_{\text{built-in}}$ is approximately equal to the band-gap voltage of the doped regions ($\approx 1.5$ V for a GaAs diode).

Figure 42.7 gives a schematic band diagram of a quantum well with a strong DC electric field applied. The field tilts the potential and distorts the wave function as the electrons tend to move towards the anode and the holes towards the cathode. This has two important consequences for the optical properties. Firstly, the lowest transition shifts to lower energies due to the electrostatic interaction between the electric dipole induced by the field and the field itself. At low fields the dipole is proportional to $F$, and the red shift is thus proportional to $F^2$ (the quadratic Stark effect). At higher fields, the dipole saturates at a value limited by $ed$, where $e$ is the electron charge and $d$ the well width, and the Stark shift is linear in $F$. Secondly, the parity selection rule no longer applies due to the breaking of the inversion symmetry about the centre of the well. This means that forbidden transitions with $\Delta n$ equal to an odd number become allowed. At the same time, the $\Delta n = 0$ transitions gradually weaken with increasing field as the distortion to the wave functions reduces the electron–hole overlap.

Figure 42.8 shows the normalised room-temperature photocurrent spectra of a GaAs/Al$_{0.3}$Ga$_{0.7}$As MQW p–i–n diode containing 9.0-nm quantum wells at 0 V and $-10$ V applied bias. These two bias values correspond to field strengths of around 15 kV/cm and 115 kV/cm respectively. The photocurrent spectrum closely resembles the absorption spectrum, due to the field-induced escape of the photoexcited carriers in the QWs into the external circuit (Sect. 42.2.5). The figure clearly shows the Stark shift of the absorption edge at the higher field strength, with a red shift of around 20 meV (≈ 12 nm) at $-10$ V bias for the hh$_1 \rightarrow$ e$_1$ transition. The intensity of the line weakens somewhat due to the reduction in the electron–hole overlap, and there is lifetime broadening caused by the field-assisted tunnelling. Several parity-forbidden transitions are clearly observed. The two most obvious ones are identified with arrows, and correspond to the hh$_2 \rightarrow$ e$_1$ and hh$_1 \rightarrow$ e$_2$ transitions, respectively.

A striking feature in Fig. 42.8 is that the exciton lines are still resolved even at very high field strengths. In bulk GaAs the excitons ionise at around 5 kV/cm [42.11], but in QWs the barriers inhibit the field ionisation, and excitonic features can be preserved even up to $\approx 300$ kV/cm [42.14]. The ability to control the absorption spectrum by the QCSE is the principle behind a number of important modulator devices, which will be discussed in Sect. 42.5.

In the case of a superlattice, such as that illustrated in Fig. 42.9, a strong perpendicular electric field can break the minibands into discrete energy levels local to each QW, due to the band-gap tilting effect represented in Fig. 42.7. The possibility of using an electric field to modify the minibands of a superlattice is yet another remarkable ability of band-gap engineering to achieve control over the electronic properties by directly using fundamental principles of quantum mechanics.

### 42.2.4 Inter-Sub-Band Transitions

The engineered band structure of quantum wells leads to the possibility of *inter-sub-band (ISB) transitions*, which take place between confined states within the conduction or valence bands, as illustrated schematically in Fig. 42.9. The transitions typically occur in the infrared spectral region. For example, the e$_1 \leftrightarrow$ e$_2$ ISB transition in a 10-nm GaAs/AlGaAs quantum well occurs at around 15 μm. For ISB absorption transitions we must first dope the conduction band so that there is a large population of electrons in the e$_1$ level, as shown
and final confined levels. The parity of the parallel to the growth direction. Furthermore, the odd indicates that the electric field of the light wave must be bracket arises from the electric-dipole interaction and as either electronic devices. The transport is generally classified as either unipolar or bipolar. The only material-dependent parameter that enters the ISB transitions in infrared emitters and detectors will be discussed in Sects. 42.3.2, 42.4.3 and 42.4.4.

42.2.5 Vertical Transport

Quantum Wells

Vertical transport refers to the processes by which electrons and holes move in the growth direction. Issues relating to vertical transport are important for the efficiency and frequency response of most QW optoelectronic devices. The transport is generally classified as either bipolar, when both electrons and holes are involved, or unipolar, when only one type of carrier (usually electrons) is involved. In this section we will concentrate primarily on bipolar transport in QW detectors and QCSE modulators. Bipolar transport in light-emitting devices is discussed in Sects. 42.2.6 and 42.3.1, while unipolar transport in quantum cascade lasers is discussed in Sect. 42.3.2.

In QW detectors and QCSE modulators the diodes are operated in reverse bias. This produces a strong DC electric field and tilts the bands as shown in Fig. 42.7. Electrons and holes generated in the quantum wells by absorption of photons can escape into the external circuit by tunnelling and/or thermal emission, as illustrated schematically in Fig. 42.7.

The physics of tunnelling in quantum wells is essentially the same as that of α-decay in nuclear physics. The confined particle oscillates within the well and attempts to escape every time it hits the barrier. The escape rate is proportional to the attempt frequency \( v_0 \) and the transmission probability of the barrier. For the simplest case of a rectangular barrier of thickness \( b \), the escape time \( \tau_T \) is given by:

\[
\frac{1}{\tau_T} = v_0 \exp(-2\kappa b),
\]

where \( \kappa \) is the tunnelling decay constant given by (42.10). The factor of 2 in the exponential arises due to the dependence of the transmission probability on \( |\psi(z)|^2 \). The situation in a biased quantum well is more complicated due to the non-rectangular shape of the barriers. However, (42.23) allows the basic trends to be understood. To obtain fast tunnelling we need thin barriers and small \( \kappa \). The second requirement is achieved by keeping \( m^* \) as small as possible and by working with a small confining potential \( V_0 \). The tunnelling rate increases with increasing field, because the average barrier height decreases.

The thermal emission of electrons over a confining potential is an old problem which was originally applied to the heated cathodes in vacuum tubes. It has been shown that the thermal current fits well to the classical Richardson formula:

\[
J_0 \propto T^{1/2} \exp\left(-\frac{e\Phi}{k_B T}\right),
\]

with the work function \( \Phi \) replaced by \( [V(F) - E_a] \). \( V(F) \) being the height of the barrier that must be overcome at the field strength \( F \) [42.15]. The emission rate is dominated by the Boltzmann factor, which represents the probability that the carriers have enough thermal kinetic energy to escape over the top of the barrier. At low fields \( V(F) \approx (V_0 - E_a) \), but as the field increases, \( V(F) \) decreases as the barriers tilt over. Hence the emission rate (like the tunnelling rate) increases with increasing field. The only material-dependent parameter that enters the Boltzmann factor is the barrier height. Since this is insensitive both to the effective masses and to the barrier
42.2 Optoelectronic Properties of Quantum-Confined Structures

Fig. 42.10 Schematic representation of the drift of injected carriers and their subsequent capture by quantum wells. Light emission occurs when electrons and holes are captured in the same quantum well and then recombine with each other.

The carrier capture and subsequent relaxation of the carriers is thus of crucial importance. Let us consider the band-edge profile of a typical QW diode-laser active region, as illustrated in Fig. 42.10. The active region is embedded between larger band-gap cladding layers designed to prevent thermally assisted carrier leakage outside the active region. Electrons and holes are injected from the n- and p-doped cladding layers under forward bias and light emission follows after four distinct processes have taken place: (1) relaxation of carriers from the cladding layers to the confinement barriers (CB); (2) carrier transport across the CB layers, by diffusion and drift; (3) carrier capture into the quantum wells; and (4) carrier relaxation to the fundamental confined levels.

The carrier relaxation to the CB layers occurs mainly by longitudinal optical (LO) phonon emission. The CB layer transport is governed by a classical electron fluid model. The holes are heavier and less mobile than the electrons, and hence the ambipolar transport is dominated by the holes. Carrier nonuniformities, such as carrier pile up at the p-side CB region due to the lower mobility of the holes, are taken into account in the design of the barrier layers. The carrier capture in the QWs is governed by the phonon-scattering-limited carrier mean free path. It is observed experimentally that the capture time oscillates with the QW width. Detailed modelling reveals that this is related to a resonance between the LO phonon energy and the energy difference between the barrier states and the confined states within the well [42.21]. As another design guideline, the QW widths must be larger or at least equal to the phonon-scattering-limited carrier mean free path at the operating temperature in order to speed up the carrier capture. Finally, the relaxation of carriers to the lowest sub-band occurs on a sub-picosecond time scale if the inter-sub-band energy separation is larger than the LO phonon energy. Carrier–carrier scattering can also contribute to an ultrafast thermalisation of carriers, on a femtosecond time scale at the high carrier densities present inside laser diodes. Many of these processes have been studied in detail by ultrafast laser spectroscopy [42.22].

Carrier capture and escape are complementary vertical transport mechanisms in MQW structures. In the design of vertical transport-based MQW devices, one process must often be sped up at the expense of making the other as slow as possible. For example, in order to enhance the performance of QW laser diodes, the carrier confinement capability of the MQW active region must be optimised in terms of minimising the ratio between the carrier capture and escape times [42.23].
42.3 Emitters

42.3.1 Interband Light-Emitting Diodes and Lasers

Quantum wells have found widespread use in light-emitting diode (LED) and laser diode applications for a number of years now. As discussed in Sects. 42.1.2 and 42.2.2, there are three main reasons for this. Firstly, the ability to control the quantum-confinement energy provides an extra degree of freedom to engineer the emission wavelength. Secondly, the change of the density of states and the enhancement of the electron–hole overlap leads to superior performance. Finally, the ability to grow strained layers of high optical quality greatly increases the variety of material combinations that can be employed, thus providing much greater flexibility in the design of the active regions.

Much of the early work concentrated on lattice-matched combinations such as GaAs/AlGaAs on GaAs substrates. GaAs/AlGaAs QW lasers operating around 800 nm has now become industry-standard for applications in laser printers and compact discs. Furthermore, the development of high-power arrays has opened up new applications for pumping solid-state lasers such as Nd : YAG. Other types of lattice-matched combinations can be used to shift the wavelength into the visible spectral region and also further into the infrared. QWs based on the quaternary alloy (Al$_y$Ga$_{1-y}$)$_x$In$_{1-x}$P, are used for red-emitting laser pointers [42.24], while Ga$_{0.47}$In$_{0.53}$As QWs and its variants incorporating Al are used for the important telecommunication wavelengths of 1300 nm and 1550 nm.

The development of strained-layer QW lasers has greatly expanded the range of material combinations that are available. The initial work tended to focus on In$_x$Ga$_{1-x}$As/GaAs QWs grown on GaAs substrates. The incorporation of indium into the quantum well shifts the band edge to lower energy, thereby giving emission in the wavelength range 900–1100 nm. An important technological driving force has been the need for powerful sources at 980 nm to pump erbium-doped fibre amplifiers [42.25]. Furthermore, as mentioned in Sect. 42.2.1, the strain alters the band structure and this can have other beneficial effects on the device performance. For example, the compressive strain in the In$_x$Ga$_{1-x}$As/GaAs QW system has been exploited in greatly reducing the threshold current density. This property is related to the reduced effective mass of the holes and hence the reduced density of states. An extensive account of the effects of strain on semiconductor layers and the performance of diode lasers is given in [42.26].

At the other end of the spectral range, a spectacular development has been the In$_x$Ga$_{1-x}$N/GaN QWs grown on sapphire substrates. These highly strained QWs are now routinely used in ultrabright blue and green LEDs, and there is a growing interest in developing high-power LED sources for applications in solid-state lighting [42.27]. Commercial laser diodes operating around 400 nm have been available for several years [42.8], and high-power lasers suited to applications in large-capacity optical disk video recording systems have been reported [42.28]. Lasers operating out to 460 nm have been demonstrated [42.29], and also high-efficiency ultraviolet light-emitting diodes [42.30]. At the same time, much progress has been made in the application of AlGaN/GaN quantum-well materials in high-power microwave devices [42.31, 32].

A major application of quantum wells is in vertical-cavity surface-emitting lasers (VCSELs). These lasers emit from the top of the semiconductor surface, and have several advantages over the more-conventional edge-emitters: arrays are readily fabricated, which facilitates their manufacture; no facets are required, which avoids complicated processing procedures; the beam is circular, which enhances the coupling efficiency into...
optical fibres; and their small size leads to very low threshold currents. For these reasons the development of VCSELs has been very rapid, and many local-area fibre networks operating around 850 nm currently employ VCSEL devices. This would not have been possible without the high gain coefficients that are inherent to the QW structures.

Figure 42.11 gives a schematic diagram of a typical GaAs-based VCSEL. The device contains an active QW region inserted between two distributed Bragg reflector (DBR) mirrors consisting of AlGaAs quarter-wave stacks made of alternating high- and low-refractive-index layers. The structure is grown on an n-type GaAs substrate, and the mirrors are appropriately doped n- or p-type to form a p–n junction. Electrons and holes are injected into the active region under forward bias, where they are captured by the QWs and produce gain at the lasing wavelength $\lambda$. The quantum wells are contained within a transparent layer of thickness $\lambda/2n_0$, where $n_0$ is the average refractive index of the active region. The light at the design wavelength is reflected back and forth through the gain medium and adds up constructively, forming a laser resonator. Oxidised or proton-implanted regions provide lateral confinement of both the current and the optical mode. Reviews of the design and properties of VCSELs may be found in [42.34] and [42.35].

The conventional VCSEL structures grown on GaAs substrates operate in the wavelength range 700–1100 nm [42.36]. Some of these structures are lattice-matched, but others – notably the longer-wavelength devices which incorporate strained InGaAs quantum wells – are not. Much work is currently focussed on extending the range of operation to the telecommunication wavelengths of 1300 nm and 1550 nm. Unfortunately, it is hard to grow DBR mirrors with sufficient reflectivity on InP substrates due to the low refractive-index contrast of the materials, and thus progress has been slow. Recent alternative approaches based on GaAs substrates will be mentioned in Sect. 42.6.

Resonator structures such as the VCSEL shown in Fig. 42.11 can be operated below threshold as resonant-cavity LEDs (RCLEDs). The presence of the cavity reduces the emission line width and hence increases the intensity at the peak wavelength [42.37]. Furthermore, the narrower line width leads to an increase in the bandwidth of the fibre communication system due to the reduced chromatic dispersion [42.38]. A review of the progress in RCLEDs is given in [42.39].

### 42.3.2 Quantum Cascade Lasers

The principles of infrared emission by ISB transitions were described in Sect. 42.2.4. Electrons must first be injected into an upper confined electron level as shown in Fig. 42.9b. Radiative transitions to lower confined states with different parities can then occur. ISB emission is usually very weak, as the radiative transitions have to compete with very rapid nonradiative decay by phonon emission, (Sect. 42.2.6). However, when the electron density in the upper level is large enough, population inversion can occur, giving rapid stimulated emission and subsequent laser operation. This is the operating concept of the quantum cascade (QC) laser first demonstrated in 1994 [42.40]. The laser operated at 4.2 $\mu$m at temperatures up to 90 K. Although the threshold current for the original device was high, progress in the field has been very rapid. A comprehensive review of the present state of the art is given in [42.33], while a more introductory overview may be found in [42.41].

![Conduction band diagram for two active regions of an InGaAs/AlInAs quantum cascade laser, together with the intermediate miniband injector region. The levels in each active region are labelled according to their quantum number $n$, and the corresponding wave function probability densities are indicated. Laser transitions are indicated by the wavy arrows, while electron tunnelling processes are indicated by the straight arrows. (After [42.33], @ 2001 IOP) ](image)

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The quantum-well structures used in QC lasers are very complicated, and often contain hundreds of different layers. Figure 42.12 illustrates a relatively simple design based on lattice-matched In$_{0.47}$Ga$_{0.53}$As/Al$_{0.48}$In$_{0.52}$As quantum wells grown on an InP substrate. The diagram shows two active regions and the miniband injector region that separates them. A typical operational laser might contain 20–30 such repeat units. The population inversion is achieved by resonant tunnelling between the \( n = 1 \) ground state of one active region and the \( n = 3 \) upper laser level of the next one. The basic principles of this process were enunciated as early as 1971 [42.42], but it took more than 20 years to demonstrate the ideas in the laboratory. The active regions contain asymmetric coupled quantum wells, and the laser transition takes place between the \( n = 2 \) and \( n = 1 \) levels is carefully designed to coincide with the LO-phonon energy, so that very rapid relaxation to the ground state occurs and the system behaves as a four-level laser. This latter point is crucial, since the lifetime of the upper laser level is very short (typically \( \approx 1 \) ps), and population inversion is only possible when the lifetime of the lower laser level is shorter than that of the upper one. The lasing wavelength can be varied by detailed design of the coupled QW active region. The transition energy for the design shown in Fig. 42.12 is 0.207 eV, giving emission at 6.0 \( \mu \)m. Further details may be found in [42.33].

A very interesting recent development has been the demonstration of a QC laser operating in the far-infrared spectral region at 67 \( \mu \)m [42.43]. Previous work in this spectral region had been hampered by high losses due to free-carrier absorption and the difficulties involved in designing the optical waveguides. The device operated up to 50 K and delivered 2 mW. These long-wavelength devices are required for applications in the THz frequency range that bridges between long-wavelength optics and high-frequency electronics.

### 42.4 Detectors

Photodetectors for the visible and near-infrared spectral regions are generally made from bulk silicon or III–V alloys such as GaInAs. Since these devices work very well, the main application for QW photodetectors is in the infrared spectral region and for especially demanding applications such as avalanche photodiodes and solar cells. These three applications are discussed separately below, starting with solar cells.

#### 42.4.1 Solar Cells

The power generated by a solar cell is determined by the product of the photocurrent and the voltage across the diode. In conventional solar cells, both of these parameters are determined by the band gap of the semiconductor used. Large photocurrents are favoured by narrow-gap materials, because semiconductors only absorb photons with energies greater than the band gap, and narrow-gap materials therefore absorb a larger fraction of the solar spectrum. However, the largest open-circuit voltage that can be generated in a p–n device is the built-in voltage which increases with the band gap of the semiconductor used. Quantum-well devices can give better performance than their bulk counterparts because they permit separate optimisation of the current- and voltage-generating factors [42.44]. This is because the built-in voltage is primarily determined by the band gap of the barrier regions, whereas the absorption edge is determined by the band gap of the quantum wells. The drawback in using quantum wells is that it is difficult to maintain high photocurrent quantum efficiency in the low-field forward-bias operating conditions in solar cells.

Recent work in this field has explored the added benefits of the versatility of the design of the QW active region [42.45] and also the possibility of using strained QWs. In the latter case, a tradeoff arises between the increase in both the absorption and the number of interface dislocations (which act as carrier traps) with the number of QWs. A way round this compromise is to use strain balance. An example is the case of In$_{x}$Ga$_{1-x}$As/GaAs$_{0.94}$P$_{0.06}$ QW solar cells grown on GaAs substrates, in which the compressive strain of the InGaAs QWs is compensated with the tensile-strained GaAs$_{0.94}$P$_{0.06}$ barriers, such that the overall active region could be successfully lattice-matched to the substrate [42.46].

#### 42.4.2 Avalanche Photodiodes

Avalanche photodiodes (APDs) are the detectors of choice for many applications in telecommunications and single-photon counting. The avalanche multiplica-
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- **Fig. 42.13** Schematic representation of an InGaAs/InP/InGaAsP/InAlAs superlattice avalanche photodiode (SL-APD). Light is absorbed in the bulk InGaAs layer and the resulting photocurrent is multiplied by the avalanche process in the InGaAsP/InAlAs superlattice region. The spatial periodicity of the superlattice reduces the dark current.

The principles of infrared absorption by ISB transitions were described in Sect. 42.2.4. Infrared detectors are required for applications in defence, night vision, astronomy, thermal mapping, gas-sensing, and pollution monitoring. Quantum-well inter-sub-band photodetectors (QWIPs) are designed so that the energy separation of the confined levels is matched to the chosen wavelength. A major advantage of QWIPs over the conventional approach employing narrow-gap semiconductors is the use of mature GaAs-based technologies. Furthermore, the detection efficiency should in principle be high due to the large oscillator strength that follows from the parallel curvature of the in-plane dispersions for states within the same bands [42.56]. However, technical challenges arise from the requirement that the electric field of the light must be polarised along the growth (z) direction. This means that QWIPs do not work at normal incidence, unless special steps are taken to introduce a component of the light field along the z-direction. Various approaches have been taken for optimum light coupling, such as using bevelled edges, gratings or random reflectors [42.57].

Despite their promising characteristics, QWIPs have yet to be commercialised. The main issue is the high dark current at higher operating temperatures. The dark current is governed by the thermionic emission of ground-state electrons directly out of the QW above 45 K [42.58]. Overcoming such technical difficulties has made possible the demonstration of long-wavelength large-format focal-plane array cameras based on ISB transitions [42.59].

42.4.4 Unipolar Avalanche Photodiodes

The combination of resonant inter-sub-band (ISB) photodetection (Sect. 42.4.3) and avalanche multiplication has been studied for exploiting the possibility of designing a unipolar avalanche photodiode (UAPD) [42.60]. UAPDs rely on impact ionisation involving only one
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Fig. 42.14 Unipolar carrier multiplication in a multiple QW structure at field strength $F$: (1) is the primary electron resulting from photodetection, while (2) is the secondary electron resulting from the impact ionisation of the QW by the primary electron.

type of carrier in order to achieve gain in photoconductive detectors for mid- and far-infrared light. The unipolar impact ionisation occurs when the kinetic energy of the primary carrier exceeds an activation energy $E_a$ defined as the transition energy between the QW ground state and the QW top state (Fig. 42.14). A single QW then releases an extra electron each time it is subject to an impact with an incoming electron.

The impact ionisation probability for this process is given by the product between the carrier capture probability and the carrier escape probability under a mechanism of carrier–carrier scattering in the QW. The subsequent electron transport towards further multiplication events occurs through a sequence of escape, drift and kinetic energy gain under the applied electric field, relaxation, capture and QW ionisation. Ultimately, the multiplication gain in an UAPD is governed by the QW capture probability, the number of QWs and the field uniformity over the QW sequence. The unipolar nature of the multiplication process must be preserved in order to avoid field nonuniformities stemming from spatial-charge variation caused by bipolar carrier transport across the multiplication region.

Interest in a purely unipolar multiplication mechanism was originally motivated by the possibility of reduced noise in comparison to bipolar APDs (Sect. 42.4.2), where band-to-band transitions lead to gain fluctuations manifested as excess noise [42.55]. For this purpose, the QWs in an UAPD structure are typically tailored such that the inter-sub-band activation energy $E_a$ is smaller than the inter-band impact ionisation activation energy that would be responsible for bipolar avalanche multiplication. However, recent studies have shown that unipolar avalanche multiplication is also accompanied by an excess noise factor, such that the noise gain exceeds the photoconductive gain [42.61], thus limiting the practical applications of UAPDs.

42.5 Modulators

In Sect. 42.2.3 we noted that the optical properties of quantum-well diodes are strongly modified by the application of voltages through the quantum-confinement Stark effect (QCSE). Referring to Fig. 42.8, we see that at wavelengths below the heavy-hole exciton at 0 V, the absorption increases as the voltage is applied, which provides a mechanism for the modulation of light. For example, the amount of light transmitted at wavelengths close to the band edge would change with the voltage applied. Moreover, since changes of absorption are accompanied by changes of the refractive index through the Kramers–Kronig relationship, it is possible to make QCSE phase modulators as well [42.62]. In addition to the standard GaAs/AlGaAs devices operating around 800 nm, QCSE modulators have been demonstrated in several other material systems, such as GaInAs-based structures for the important telecommunications wavelength at 1.5 μm [42.63].

The operation of GaAs-based QCSE transmission modulators at normal incidence is hampered by the fact that the substrates are opaque at their operating wavelength. One way round this problem of both the high substrate losses and the waveguide thickness limitation is to make use of quantum-well waveguides with interdigital Bragg gratings, and distributed feedback lasers. In this configuration, the laser and the modulator are separated by proton implantation. The light emitted by the laser is guided through the EAM region, resulting in a modulated output beam when data pulses are applied to the EAM.
is to etch the substrate away, but this is a difficult process, and a much better solution is to include a mirror underneath the quantum wells so that the modulated light does not have to pass through the substrate [42.64]. In many practical applications, however, mostly involving the integration of QCSE modulators with MQW light emitters on a common substrate, the waveguide geometry is the configuration of choice [42.65]. In this architecture, the light beam propagates along the waveguide from the emitter to the electroabsorption modulator (EAM) region, as shown in Fig. 42.15. The QCSE modulator transmits the incoming laser light when no voltage is applied and absorbs the beam when the MQW stack is suitably biased.

The most successful commercial impact of QCSE modulators has been in the integration of EAMs with distributed feedback (DFB) or distributed Bragg reflector (DBR) MQW diode lasers in waveguide configurations, as shown in Fig. 42.15. These devices have been used for optical coding in the C-band (1525–1565 nm), at 10 Gb/s or higher data transmission speeds [42.66]. The combination of a continuous laser and a high-speed modulator offers better control of the phase chirp of the pulses than direct modulation of the laser output itself [42.67]. In particular, the chirp factor is expected to become negative if the photogenerated carriers can be swept out fast enough in the EAM, which is desirable for long-distance data transmission through optical fibers [42.68].

A promising step toward the merger between band-gap-engineered semiconductors and mature very-large-scale integration (VLSI) silicon architectures has been achieved when III–V semiconductor QCSE modulator structures have been integrated with state-of-the-art silicon complementary metal–oxide–semiconductor (CMOS) circuitry [42.69]. Through this hybrid technology, thousands of optical inputs and outputs could be provided to circuitry capable of very complex information processing. The idea of using light beams to replace wires in telecommunications and digital computer systems has thus become an attractive technological avenue in spite of various challenges implied [42.70].

42.6 Future Directions

The subject of quantum-confined semiconductor structures moves very rapidly and it is difficult to see far into the future. Some ideas have moved very quickly from the research labs into the commercial sector (e.g. VCSELs), while others (e.g. quantum cascade lasers) have taken many years to come to fruition. We thus restrict ourselves here to a few comments based on active research fields at the time of writing.

One idea that is being explored in detail is the effects of lower dimensionality in quantum-wire and quantum-dot structures (Table 42.1). Laser operation from one-dimensional (1-D) GaAs quantum wires was first demonstrated in 1989 [42.72], but subsequent progress has been relatively slow due to the difficulty in making the structures. By contrast, there has been an explosion of interest in zero-dimensional (0-D) structures following the discovery that quantum dots can form spontaneously during MBE growth in the Stranski–Krastanow regime. A comprehensive review of this subject is given in [42.73].

Figure 42.16 shows an electron microscope image of an InAs quantum dot grown on a GaAs crystal by the Stranski–Krastanow technique. The dots are formed because of the very large mismatch between the lattice constants of the InAs and the underlying GaAs. The strain that would be produced in a uniform layer is so large that it is energetically favourable to form small clusters. This then leads to the formation of islands of InAs with nanoscale dimensions, which can then be encapsulated within an optoelectronic structure by overgrowth of further GaAs layers.

The ability to grow quantum-dot structures directly by MBE has led to very rapid progress in the deployment of quantum dots in a variety of applications. It remains unclear at present whether quantum dots really lead to superior laser performance [42.74]. The intrin-
sic gain of the dots is higher than that of a quantum well [42.75], and the threshold current is less sensitive to temperature [42.76]. However, the volume of the gain medium is necessarily rather small, and the benefits of the lower dimensionality cannot be exploited to the full. At present, one of the most promising applications for quantum dots is in long-wavelength lasers [42.77]. As mentioned in Sect. 42.3.1, the production of VCSELs at 1300 nm and 1550 nm has proven to be difficult using conventional InP-based QW structures due to the low refractive-index contrast of the materials that form the DBR mirrors. The use of InAs/GaAs quantum dots as the active region circumvents this problem and allows the benefits of mature GaAs-based VCSEL technology.

Another very exciting potential application for quantum dots is in quantum information processing. High-efficiency single-photon sources are required for quantum cryptography and also quantum computation using linear optics. Several groups have demonstrated single photon emission after excitation of individual InAs quantum dots (see e.g. [42.78, 79]), and one group has demonstrated an electrically driven single-photon LED [42.80]. After these proofs of principle, the challenge now lies ahead to establish the quantum-dot sources in working quantum information-processing systems.

At the same time as exploring the effects of lower dimensionality, many other groups are working on new QW materials. One of the most promising recent developments is the dilute nitride system for applications in long-wavelength VCSELs and solar cells [42.81]. It has been found that the inclusion of a small fraction of nitrogen into GaAs leads to a sharp decrease in the band gap due to very strong band-bowing effects. This then allows the growth of InGaAsN structures that emit at 1300 nm on GaAs substrates [42.77, 82]. The field is developing very rapidly, with 1300-nm VCSELs and 1500-nm edge emitters already demonstrated [42.83, 84].

42.7 Conclusions

Semiconductor quantum wells are excellent examples of quantum mechanics in action. The reduced dimensionality has led to major advances in both the understanding of 2-D physics and the applied science of optoelectronics. In some cases, QWs have enhanced the performance of conventional devices (e.g. LEDs and edge-emitting lasers), and in others, they have led to radically new devices (e.g. VCSELs, quantum cascade lasers, QCSE modulators). At present, the main commercial use for QW optoelectronic devices is in LEDs, laser diodes and QCSE modulators. It remains to be seen whether some of the other devices described here (QW solar cells, SL-APDs, QWIPs) will come to commercial fruition, and whether systems of lower dimensionality will eventually replace QWs in the same way that QWs have replaced bulk devices.

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