Chapter 29
Quantum Cascade Laser

A quantum cascade laser contains active regions and conducting regions in turn. An active region contains three electron subbands. An electron injected into the upper subband undergoes a stimulated transition to the lower subband and reaches, after a nonradiative relaxation process, the lowest subband. The electron leaves the lowest subband by spatial escape to the neighboring conducting region. Then, the electron is injected into another upper subband, undergoes another stimulated emission process, relaxes, escapes, and so on. Passing, for example, through a hundred gain regions, an electron can produce a hundred photons by stimulated transitions. A single gain region is in principle a three-level system. An electron performs a cascade of stimulated emission processes in subsequent three-level systems.

How can we obtain a gain region in a quantum cascade laser and how can we inject an electron into a gain region and extract an electron from a gain region?

We can realize a gain region by the use of coupled quantum wells. Tunnel splitting of energy levels leads to appropriate subbands. Superlattices connect next-near gain regions. Injection of electrons into a gain region and extraction of electrons from a gain region are due to tunneling processes under the action of a static electric field.

The quantum cascade laser operating at room temperature is a radiation source of the infrared; it is available at wavelengths just beyond the wavelengths of bipolar lasers, from about 2–28 μm (11–150 THz). Quantum cascade lasers cooled to liquid nitrogen temperature operate in the frequency range of about 1–5 THz.

It is expected that terahertz radiation may be of importance for applications in the areas of communications, the environment, medicine, and security. Pioneering work is done in infrared and millimeter wave astronomy through the use of oscillators as local oscillators of heterodyne detectors (that are most sensitive).

K.F. Renk, *Basics of Laser Physics*, Graduate Texts in Physics,
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29.1 Principle of the Quantum Cascade Laser

The quantum cascade laser (QCL) is a three-level laser. The three levels (Fig. 29.1a) belong to subband 0, subband 1, and subband 2. Under the action of a static field E_s, electrons are injected into the subband 2 and perform stimulated transitions to subband 1. The subband 1 is depopulated by relaxation via the emission of phonons and the subband 0 is depopulated by the spatial extraction of electrons. In principle, an electron passing through a subband system with 100 periods can produce 100 photons! Injection occurs by means of a conducting superlattice. In the superlattice region, the energy of an electron is energetically constrained to a miniband, i.e., to an energy band that is much smaller than an energy band of a bulk semiconductor. Extraction occurs to another superlattice. A spatial period is repeated about 100 times or more (Fig. 29.1b).

An external voltage, leading to a voltage U_1 per period, drives the electron through the cascade system. The voltage per period is approximately

$$U_1 \approx E_2 - E_0, \tag{29.1}$$

where E_2, E_1, and E_0 are levels belonging to the three subbands. The quantum efficiency $\eta_q \approx (E_2 - E_1)/(E_2 - E_0)$ have a value near 1. The overall power efficiency can be larger than 0.5.

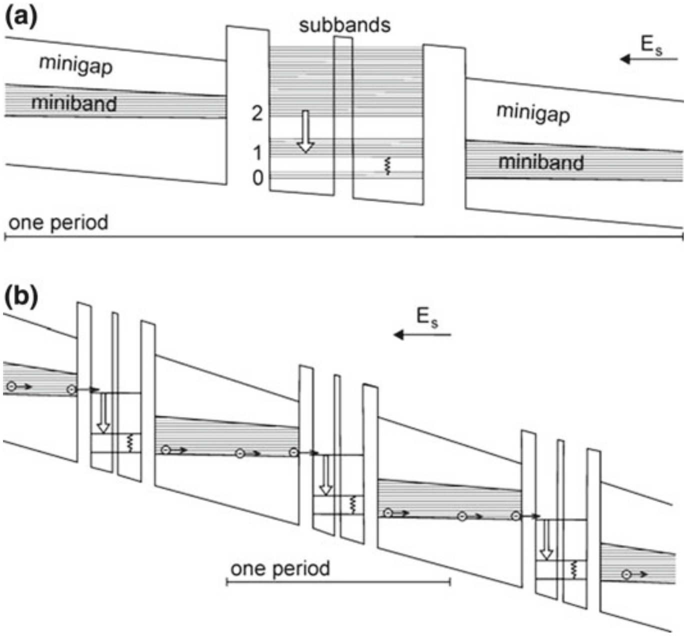


Fig. 29.1 Quantum cascade laser. **a** Single period and **b** three periods (*out of a hundred periods*)

Under the action of a static field, an electron propagates through a miniband, then through a tunnel barrier into the active region with the three subbands and, after an optical transition and relaxation, into another miniband. The active region contains two coupled quantum wells. A narrow tunnel barrier between the wells provides the coupling.

A minigap (a gap between two minibands) prevents the tunneling of electrons out of the subband 2. Perpendicular to the heterostructure, the electrons can move freely. The injector consists of a miniband, with a continuously decreasing miniband width, realized by quantum film layers and quantum well layers in turn (Sect. 29.3).

The heterostructure of a quantum cascade laser can be grown by molecular epitaxy.

29.2 Infrared Quantum Cascade Laser

The infrared quantum cascade laser (Fig. 29.2) consists of a quantum cascade heterostructure on a conducting substrate (GaP or GaAs). The heterostructure contains conduction electrons ($\sim 10^{22}$ m^{-3}), introduced into the heterostructure during its preparation by doping with silicon. An electric power of the order of 1 W (voltage 5 V; current 0.2 A) leads (in a structure of 1 mm length; 100 μm width; 10 μm thickness) to radiation of a power of several mW.

Room temperature QCLs and low temperature QCLs cover different wavelength regions.

- 2–28 μm; InGaAs/InAlAs heterostructure grown on GaP substrate; operation at room temperature; power 1–100 mW.
- 60–360 μm; GaAs/GaAlAs heterostructures grown on a GaAs substrate; operation at the temperature of liquid nitrogen; power 1–10 mW.

Before discussing the far infrared quantum cascade laser, we introduce superlattices and minibands.

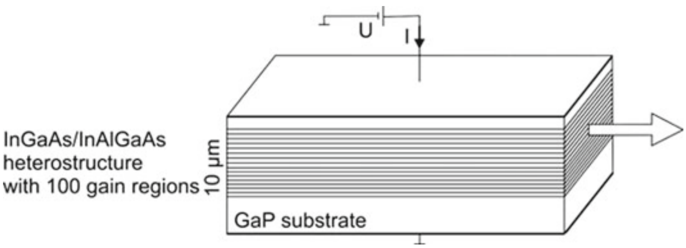


Fig. 29.2 Quantum cascade laser

29.3 Semiconductor Superlattice and Minibands

Semiconductor superlattices with minibands play an important role for quantum cascade lasers. We describe here properties of a GaAs/AlAs superlattice.

A GaAs/AlAs superlattice (Fig. 29.3) consists of a periodic sequence of GaAs layers and AlAs layers. An electron propagating along the superlattice axis experiences the AlAs layers as potential barriers. The periodic potential leads to minibands separated by minigaps. We characterize the dispersion relation of electrons in the lowest miniband by:

$$\epsilon = \epsilon_{\mathrm{m}} \left(\frac{1}{2} - \frac{1}{2} \cos\, k_x a \right), \tag{29.2}$$

where ϵ is the energy, ϵ_{m} is the miniband width and k_x the wave vector along the superlattice axis. The dispersion curve is periodic in k_x. Therefore, we can restrict the wave vector k_x to the mini-Brillouin zone $-\pi/a < k_x \le \pi/a$. The calculation of minibands is possible by the use of a Kronig–Penney model (Chap. 30).

The motion perpendicular to the superlattice axis, within the GaAs layers, corresponds to a free motion of a conduction electron. The energy of a miniband electron is given by

$$E = E_{\mathrm{c}} + E_{\mathrm{zp}} + \epsilon_{\mathrm{m}} \left(\frac{1}{2} - \frac{1}{2} \cos k_x a \right) + \frac{\hbar^2 (k_y^2 + k_z^2)}{2m_{\mathrm{c}}}. \tag{29.3}$$

E_{c} is the energy of an electron at the minimum of the conduction band and E_{zp} the zero point energy of a miniband electron. The last term corresponds to the energy of motion perpendicular to the superlattice axis; m_{c} is the effective mass of an electron in the minimum of the conduction band of GaAs.

The value of ϵ_{m} of a GaAs/AlAs superlattice is adjustable by the choice of the period a of the superlattice and of the width of the AlAs barrier layers. The largest

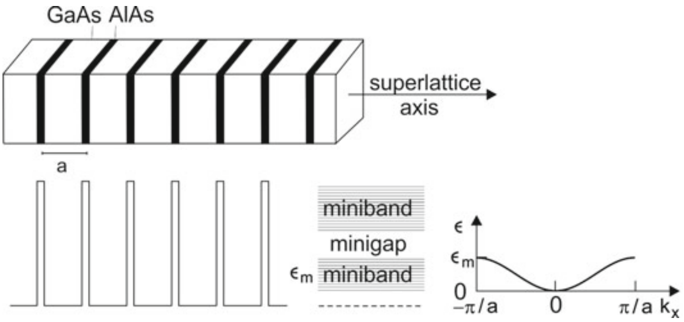


Fig. 29.3 GaAs/AlAs superlattice and minibands

value of the miniband width of a GaAs/AlAs superlattice is $\epsilon_{\mathrm{m}} \sim 0.14\,\mathrm{eV}$, which corresponds to 10% of the gap energy of GaAs. InGaAs/InGaAlAs superlattices can have larger miniband widths (up to 0.3 eV) because the effective mass of a conduction electron in InAs is smaller than in GaAs.

29.4 Transport in a Superlattice

We discuss the electric transport in a superlattice (*miniband transport*). A static electric field E_{s} oriented along the superlattice axis accelerates the electrons. Relaxation gives rise to an ohmic conductivity (Fig. 29.4). The ohmic conductivity is given by

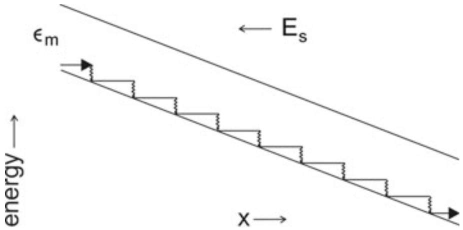
$$\sigma = \frac{N_0 e^2 \tau}{m^*}. \tag{29.4}$$

N_0 is the density of electrons in a superlattice, m^* the effective mass of an electron at the bottom of the miniband (at $k_x \approx 0$), and τ is the intraminiband relaxation time; $\tau \sim 10^{-13}$ s for an electron in a GaAs/AlAs superlattice at room temperature. The value of the effective mass m^* depends on the period of the superlattice and the barrier width. Ohmic conductivity is limited to not too strong static fields (Sect. 32.3).

In a superlattice used in a quantum cascade laser as injector (and as extractor), the layer thicknesses of GaAs and AlAs—or of InGaAs and InGaAlAs—are varying along the superlattice axis. Accordingly, the zero point energy, the widths of the minibands, and the widths of the minigaps are varying as well. An applied voltage leads to a static field along the superlattice axis. The upper boundary of the miniband limits the maximum energy an electron can reach in the static field. The first minigap prevents escape of excited electrons from the gain region as already mentioned.

Miniband transport will be treated in more detail in Sect. 32.3.

Fig. 29.4 Ohmic transport in a superlattice



29.5 Far Infrared Quantum Cascade Laser

In the far infrared quantum cascade laser (Fig. 29.5), the energy separation between sublevel 2 and sublevel 1 corresponds to a frequency in the far infrared. The energy difference between the laser levels is of the order of kT at room temperature. To reach the threshold population difference, a far infrared QCL has to be cooled, for instance to the temperature (77 K) of liquid nitrogen.

References [223–225].

Problems

29.1 Determine the frequency (and the wavelength) of laser radiation at which cooling of the active medium is favorable.

29.2 Estimate the gain (gain coefficient and gain factor per round trip) of radiation propagating in the active medium of a quantum cascade laser. [*Hint*: assume that the Einstein coefficient of stimulated emission is the same as for interband transitions.]

29.3 A quantum cascade laser cannot be realized if the laser transition frequency ν_1 coincides with the longitudinal optic frequency of the semiconductor material. Then, fast nonradiative relaxation of the upper laser level, by emission of a longitudinal optic phonon (frequency ν_{LO}) near the Brillouin zone center, makes population inversion almost impossible. Relaxation is still strong if ν_1 lies in the vicinity ν_{LO} (=8.7 THz for GaAs).

(a) Determine the frequency range for which the nonradiative lifetime of the upper laser level is shorter than 10^{-6} s, assuming that the nonradiative lifetime is 10^{-12} s at resonance ($\nu_1 = \nu_{\mathrm{LO}}$) and that the relaxation rate decreases for laser frequencies around ν_{LO} according to a Lorentz resonance function.
(b) Determine the power density in the laser medium that is necessary for reaching population inversion ($B_{21} = 4 \times 10^{21}\ \mathrm{m^3\ J^{-1}\ s^{-2}}$).

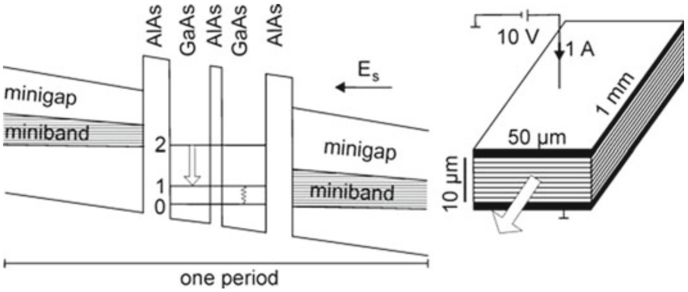


Fig. 29.5 Far infrared quantum cascade laser

(c) Discuss the influence due to thermal broadening of the electron distribution in the upper laser subband.

29.4 Strong absorption at the transversal optical frequency (=8.0 THz for GaAs) at the zone center results in damping of optical waves. In which frequency range is the optical thickness of the laser material (length 1 mm) of a quantum cascade laser larger than 0.02)? [*Hint*: assume that the absorption coefficient varies according to a Lorentz resonance function and that the absorption coefficient has a maximum value of 10^5 cm^{-1}.]