Chapter 28
A Comparison of Semiconductor Lasers

The simplest heterostructure laser is the double heterostructure laser. A GaAs double-heterostructure consists of three layers: n-doped GaAlAs; GaAs; p-doped GaAlAs. It corresponds to two heterostructures, a GaAlAs/GaAs and a GaAs/GaAlAs heterostructure that have in common the GaAs layer. The GaAs layer forms a well—not a quantum well. The well width is so large that the electrons and the holes can, in principle, move freely in all three dimensions. The double-heterostructure also acts as a light guide. The successful realization of the double heterostructure laser initiated the development of the semiconductor lasers with the more complex heterostructures that we discussed.

The junction laser (=homostructure laser = homojunction laser) was the first semiconductor laser type. A GaAs junction laser consists of an n-doped GaAs layer in direct contact to a p-doped GaAs layer. Without applied voltage, the contact (=junction) region is a depletion layer. The contact region does not contain free-electrons or free holes. A voltage applied across the junction causes a drift of electrons from the n-doped GaAs into the depletion layer and, at the same time, a drift of holes from the p-doped GaAs into the depletion layer. Recombination of electrons and holes in the depletion layer by stimulated optical transitions is the origin of laser radiation. The gain region provides a weak light guiding effect. Junction lasers, cooled to liquid nitrogen temperature, are available in the infrared spectral range up to wavelengths of about 30 μm. However, quantum cascade lasers are taking over the tasks of infrared junction lasers.

We show how the laser threshold decreased since the realization of the first semiconductor lasers.

Finally, we will present a comparison of different types of semiconductor lasers, including the quantum cascade laser (that we will discuss in the next chapter). In a spectral range—called the terahertz gap—semiconductor lasers (quantum cascade lasers) are presently in development.

Heterostructures made it possible to design artificial, spatially varying energy bands, which is the basis of the many different types of semiconductor lasers. In 1874,

K.F. Renk, *Basics of Laser Physics*, Graduate Texts in Physics,
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Ferdinand Braun introduced the *contact* between two materials as an important physical object. He found that the strength of current flowing in one direction through a contact between a metal and a conducting crystal was different from the strength of current flowing in the other direction at opposite voltage across the contact. This effect led to the first device suitable for rectification of high frequency radiation. Later, a contact between n-doped germanium and p-doped germanium was the basis of semiconductor junction transistors discovered by Bardeen, Brattain and Shockley. Making use of heterostructures instead of contacts represented an essential change in semiconductor physics. This change began by 1960 and resulted in a miniaturization of electronic devices.

28.1 Gain of Radiation in a Bulk Semiconductor

In the double heterostructure laser and the junction laser, the extensions of the active medium are large in all three dimensions. The electrons form a three-dimensional electron gas and the holes a three-dimensional hole gas.

The density of states of a three-dimensional electron gas, including the spin degeneracy, is equal to

$$D_{\mathrm{c}}(\epsilon_{\mathrm{c}}) = \frac{1}{2\pi^2}\left(\frac{2m_{\mathrm{e}}}{\hbar^2}\right)^{3/2}\epsilon_{\mathrm{c}}^{1/2}. \tag{28.1}$$

The quasi-Fermi energy of a three-dimensional electron gas follows from the relation

$$\frac{1}{2\pi^2}\left(\frac{2m_{\mathrm{e}}}{\hbar^2}\right)^{3/2}\int_0^\infty \frac{\epsilon^{1/2}\mathrm{d}\epsilon}{\exp\left[(\epsilon-\epsilon_{\mathrm{Fc}})/kT+1\right.} = N. \tag{28.2}$$

N is the density of electrons in the conduction band. For $T = 0$, we have the relation

$$\int_0^{\epsilon_{\mathrm{Fc}}} \epsilon_c^{1/2}\mathrm{d}\epsilon = \frac{2}{3}\epsilon_{\mathrm{Fc}}^{3/2} \tag{28.3}$$

and the quasi-Fermi energy is given by

$$\epsilon_{\mathrm{Fc}}(T=0) = \frac{\hbar^2}{2m_{\mathrm{e}}}(3\pi^2 N)^{2/3}. \tag{28.4}$$

The reduced density of states,

$$D_{\mathrm{r}}(\epsilon) = \frac{1}{2\pi^2}\left(\frac{2m_{\mathrm{c}}}{\hbar^2}\right)^{3/2}\epsilon^{1/2}, \tag{28.5}$$

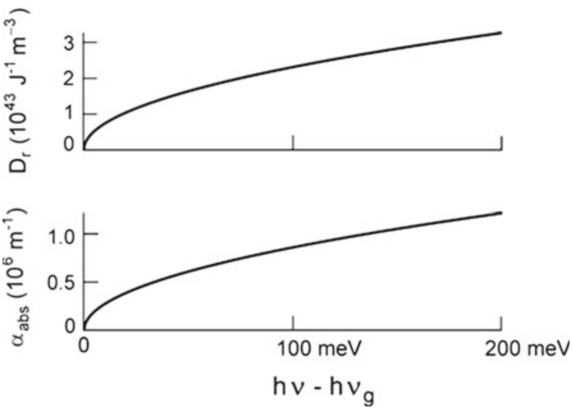

Fig. 28.1 Reduced density of states and absorption coefficient of bulk GaAs

is proportional to $\sqrt{E - E_g}$. The absorption coefficient for $T = 0$ is

$$\alpha_{abs} = \frac{n}{c} h\nu \bar{B}_{21} D_r(E_{21}). \tag{28.6}$$

Figure 28.1 shows the reduced density of states and the absorption coefficient for GaAs at $T = 0$ on the energy scale, with $h\nu = E_{21}$ and $h\nu_g = E_g$. The gain coefficient of a crystal containing nonequilibrium electrons and holes is equal to

$$\alpha = \frac{n}{c} h\nu \bar{B}_{21} D_r(E_{21})(f_2 - f_1), \tag{28.7}$$

where $f_2 = f(E_2)$, $f_1 = f_1(E_1)$, and $E_2 - E_1 = E_{21}$. Injection of electrons into the conduction band (and of holes into the valence band) of a crystal at room temperature has to be sufficiently strong to reach the transparency density. The maximum gain coefficient of GaAs at $T = 300$ K is

$$\alpha_{max} = \sigma_{eff}(N - N_{tr}), \tag{28.8}$$

where $N_{tr} \sim 2 \times 10^{24}\,\mathrm{m}^{-3}$ is the transparency density and $\sigma_{eff} = 1.5 \times 10^{-20}\,\mathrm{m}^2$ the effective gain cross section [6]. Already a small increase of N above N_{tr} results in a large gain coefficient.

Example Gain coefficient of GaAs at 300 K.

- $N_{tr} = 2 \times 10^{24}\,\mathrm{m}^{-3}$.
- $\sigma_{eff} = 1.5 \times 10^{-20}\,\mathrm{m}^2$.
- $N - N_{tr} = 0.1 \times 10^{24}\,\mathrm{m}^{-3}$.
- $\alpha_{max} = 1.5 \times 10^3\,\mathrm{m}^{-1}$.

The difference $N - N_{tr}$ is chosen so that the gain coefficient α_{max} corresponds to the threshold gain coefficient of GaAs in an edge emitting laser. The data show that a large electron density is necessary to reach transparency. A slightly larger density is sufficient to operate a laser.

28.2 Double Heterostructure Laser

As a double heterostructure laser we discuss a GaAs/GaAlAs double heterostructure laser (Fig. 28.2, left). The active zone is a GaAs well (thickness 0.2–1 μm) embedded in n-doped GaAlAs and p-doped GaAlAs. Under the action of a voltage (U), electrons migrate from the n-doped side and holes from the p-doped side into the well. This results in nonequilibrium populations of electrons in the conduction band and of holes in the valence band. Stimulated recombination of radiative electron-hole pairs leads to laser radiation.

A double heterostructure laser diode (Fig. 28.2, right) consists of different layers forming an n GaAlAs/GaAs/p GaAlAs heterostructure grown on a highly doped GaAs substrate (doped with silicon; electron concentration $2 \times 10^{24}\,\mathrm{m}^{-3}$). The GaAs layer, with a larger refractive index than the neighboring GaAlAs material, acts as a light guide. The crystal surfaces perpendicular to the light guide serve as reflectors. The threshold current is, for $N \approx N_{tr}$,

$$I_{th} \approx N_{tr} a_1 a_2 L e / \tau_{sp}. \tag{28.9}$$

Example Double heterostructure GaAs laser.

- $a_1 = 100\,\mu\mathrm{m}$; $a_2 = 0.2\,\mu\mathrm{m}$; $\mathrm{L} = 0.5\,\mathrm{mm}$.
- $G_1 V = 1$.
- $\tau_{sp} \sim 3\,\mathrm{ns}$.
- $I_{th} \sim 2.1\,\mathrm{A}$; $j_{th} \sim 2.1 \times 10^7\,\mathrm{A\,m^{-2}}$.

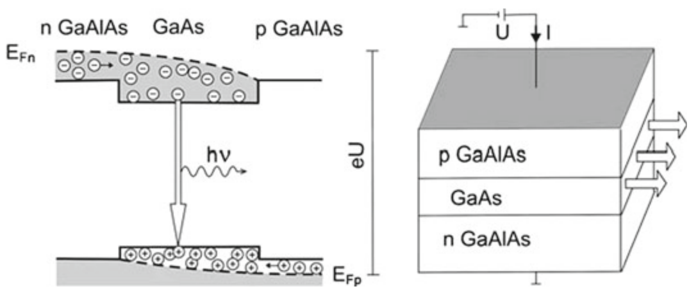

Fig. 28.2 Double heterostructure laser

The critical current is much larger than that of a quantum well laser. Below threshold, the double heterostructure emits luminescence radiation (electro-luminescence radiation). Above laser threshold, the quasi-Fermi energies of electrons and holes remain at their threshold values. Accordingly, the luminescence spectrum remains unchanged when the current exceeds the threshold current (Sect. 21.7).

28.3 GaAs Junction Laser

The junction laser (=homostructure junction laser = homojunction laser) contains nonequilibrium electrons and holes in a junction within a homogenous semiconductor material.

The GaAs junction laser (Fig. 28.3a, b) consists of a GaAs crystal, with n-doped GaAs adjacent to p-doped GaAs. A voltage (U) causes a current flow (strength I). Electrons move from one side and holes from the other side into the junction region where they recombine by emission of laser radiation. The emission wavelength of a GaAs junction laser lies in the near infrared (860 nm). Without applied voltage, the Fermi energy E_F has everywhere within the crystal the same value (Fig. 28.3c). In the junction region, there is a depletion zone (thickness ~1 μm for carrier densities of 10^{23} m^{-3} in the n-doped and the p-doped regions) in which no free carriers are present. E_{Fc} lies above E_c in n GaAs and E_{Fv} lies below E_v in p GaAs.

Example GaAs junction laser at 300 K.

- $a_1 = 100$ μm; $a_2 = 1$ μm; L = 1 mm.
- $G_1 V = 1$ at $\alpha \sim 1.5 \times 10^3\,m^{-1}$.
- $\tau_{sp} \sim 3$ ns.

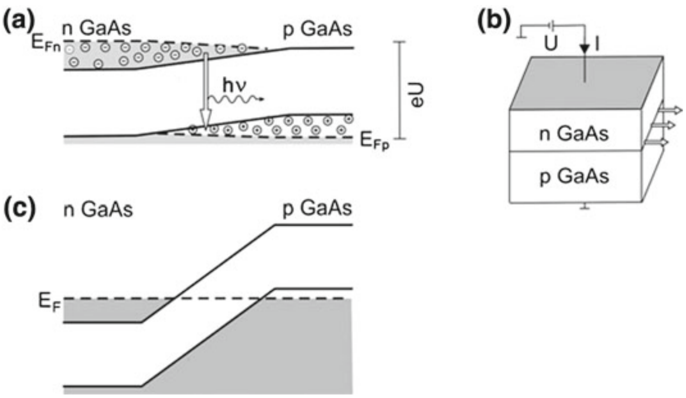

Fig. 28.3 GaAs junction laser. **a** Principle. **b** Device. **c** An n GaAs/p GaAs junction without applied voltage

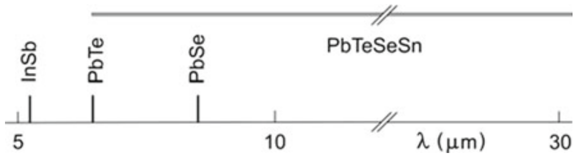

Fig. 28.4 Frequency regions of lead salt lasers

- $I_{th} \sim 10\,A$.
- $j_{th} \sim 10^8\,A\,m^{-2}$.

A junction laser operating at room temperature requires strong cooling.

In the junction laser, the active layer has a slightly larger refractive index than the surrounding n-doped GaAs and p-doped GaAs; the difference of the refractive indices is about 0.02. Therefore, there is a (weak) light guiding effect.

28.4 Junction Lasers in the Infrared

Infrared junction lasers (Fig. 28.4) consist of mixed crystals of lead salts. Lead salts have small energy gaps (PbS, $E_g \sim 270\,meV$; PbTe, 170 meV; PbSe, 130 meV). Mixed crystals of lead salts and tin salts have still smaller gap energies. The lead salt lasers operate at low temperature, at the temperature of liquid nitrogen or at lower temperature. In principle, it is possible to build a lead salt laser that generates radiation at a specific wavelength in a large range (4–30 μm). Nonradiative relaxation due to electron-hole recombination via phonons limits the wavelength range of lead salt lasers at large wavelengths.

A lead salt laser is tunable on a single mode over a very small frequency range by changing the current and the temperature.

Infrared lasers are especially suitable for detection of spurious gases (e.g., NO, NO_2) in environmental gases. Today, lead salt lasers cannot compete with quantum cascade lasers.

28.5 Bipolar Semiconductor Lasers: A Comparison

We have seen that all types of bipolar laser media are in principle suitable as active media of edge emitting lasers operating at room temperature. But there are great differences.

- The junction laser requires a large total number of electrons to reach the transparency density. Therefore, the threshold current is very large.
- The double heterojunction laser also requires a large total number of electrons. The light guiding effect is more favorable than for the junction laser.

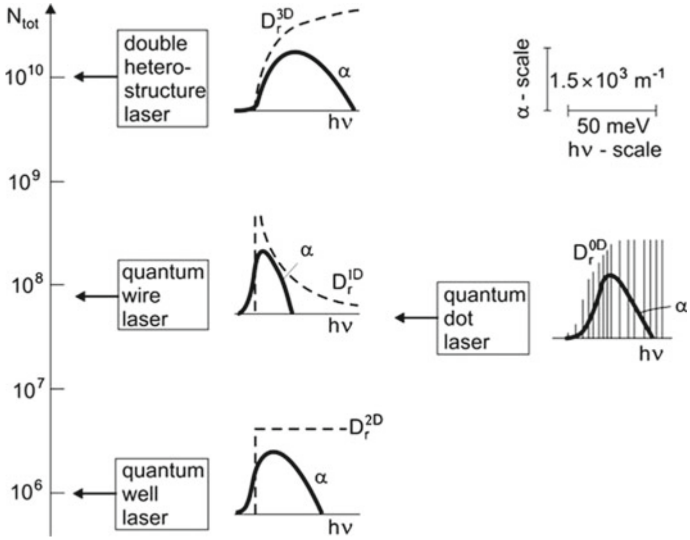

Fig. 28.5 A comparison of different bipolar semiconductor lasers at 300 K

- The quantum well laser requires a much lower total number of electrons. Preparation of quantum well lasers is possible by mass production: quantum well lasers of a high reliability are available.
- The quantum wire laser is in an early state of development.
- The quantum dot laser is being developed. The quantum dot lasers can at present not yet compete with the quantum well lasers.

We perform a quantitative comparison of different bipolar lasers operating at room temperature (Fig. 28.5). We ask how many excited electrons are necessary to drive a bipolar laser in an edge-emitting arrangement that is the same for each of the laser types ($a_1 a_2 L = 100\,\mu\text{m} \times 200\,\text{nm} \times 1\,\text{mm} = 2 \times 10^{-14}\,\text{m}^3$). The arrows indicate the total number $N_{\text{tot}} = N_{\text{tr}} a_1 a_2 L$ of electrons necessary to reach transparency density; the total number of electrons at laser threshold, $N_{\text{th,tot}}$, is only slightly (10%) larger than N_{tot}. We take into account the main broadening mechanisms. The figure shows, for each type of lasers, the shape of the reduced density of state curves $D_r(h\nu)$ and the $\alpha(h\nu)$ curves. All $\alpha(h\nu)$ curves have the same α scale and the same $h\nu$ scale. The maximum of the gain coefficient curve is equal to threshold gain coefficient. An increase of the number of excited electrons (for example, to ten times the total number at transparency) allows laser oscillation to occur at frequencies belonging to the whole gain bandwidths (=halfwidts of the gain coefficient curves). The survey indicates the following.

- *Double heterostructure laser*. Because of the three-dimensionality, a large number of electrons is necessary for the band filling.

Table 28.1 Semiconductor lasers (at a frequency around 400 THz)

Laser	N_{tot}	N_{tr}	$N_{th}/N_{tr} - 1$	N_{dot}^{2D} [N_{wire}^{2D}]	$\Delta\nu_g$ (meV)	(THz)
Qu well	10^6	$1.4 \times 10^{16}\,m^{-2}$	0.1		30	7
Qu dot	10^8		0.1	$1 \times 10^{14}\,m^{-2}$	22	5
Qu wire	10^8	$1 \times 10^8\,m^{-1}$	0.1	[$5 \times 10^6\,m^{-2}$]	17	4
Bulk	10^{10}	$2 \times 10^{24}\,m^{-3}$	0.1		40	9

- *Quantum wire laser*. A large reduced density of states (at $h\nu = E_g^{1D}$) is very favorable. However, inhomogeneous broadening caused by variation of the wire thickness distroys this advantage. The gain coefficient curve has a small width (compared to the gain curve of the junction laser and the double heterostructure laser) because the reduced density of states decreases with increasing photon energy.
- *Quantum dot laser*. The gain coefficient increases with frequency because the multiplicity of the energy levels increases with increasing quantum numbers of the energy levels. The gain curve is continuous because of inhomogeneous broadening.
- *Quantum well laser*. The quantum well laser operates with the smallest number of electrons. Because of the constant two-dimensional density of states, inhomogeneous broadening is much less effective than for the quantum wire laser and the quantum dot laser.

Table 28.1 shows data used to compare different bipolar lasers (frequency 400 THz; length L = 1 mm; crystal surfaces as reflectors; width of the active medium 100 μm; height of the photon mode 200 nm); the data have been estimated in the preceding sections or chapters. The table lists the quantities:

- N_{tot} = total number of excited electrons necessary to fulfill the threshold condition.
- N_{tr} = transparency density.
- $(N_{th} - N_{tr})/N_{tr}$ = threshold density minus transparency density, divided by the transparency density.
- N_{dot}^{2D} = two-dimensional density of quantum dots in a layer of quantum dots.
- N_{wire}^{2D} = density of quantum wires in a layer of quantum wires.
- $\Delta\nu_g$ = gain bandwidth.

28.6 Development of Semiconductor Lasers

The threshold current of semiconductor lasers (Fig. 28.6) has been strongly reduced since the first operation of a semiconductor laser in 1970. The junction laser needs the largest threshold current and has to be cooled (with few exceptions) to low temperature (100 K or lower) in order to suppress relaxation via phonons. The double heterostructure laser (since 1980) operates at room temperature. The threshold

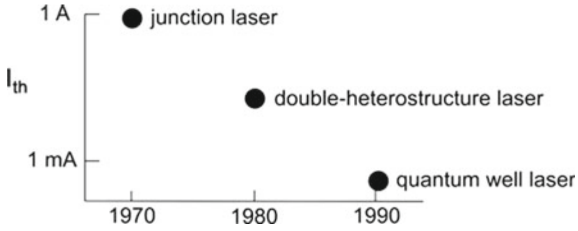

Fig. 28.6 Threshold current of bipolar semiconductor lasers operated at room temperature

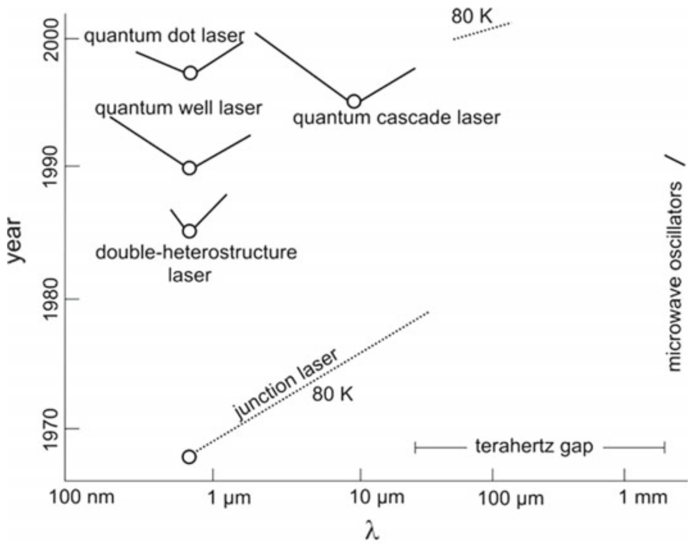

Fig. 28.7 Development of semiconductor lasers

current lies in the range of 10–100 mA. The quantum well laser reached a further remarkable decrease of the threshold current.

Together with the development of lasers of small threshold current, the reliability increased. Already in 1995, the monthly production rose to about one million laser diodes.

The development of the current-driven semiconductor lasers (Fig. 28.7) began with the junction laser. After the operation in the near infrared, the range was extended by the use of lead salt compounds into the far infrared up to a wavelength near 30 μm. In the near infrared, the junction laser, then the double heterostructure laser and the quantum well laser were introduced. The wavelength range of the quantum well laser was extended up to the near UV. In the far infrared, the junction lasers are in a large part of the spectrum replaced by the quantum cascade lasers, which generate radiation in the range from about 2–30 μm. Quantum cascade lasers, cooled to liquid nitrogen temperature, generate far infrared radiation (*see* next section).

Current-driven semiconductor lasers cover different spectral regions.

- *Near UV, visible, near infrared* (from about 0.3 to 2 µm): quantum well laser.
- *Infrared* (2–25 µm): quantum cascade laser (QCL).
- *Terahertz gap* (about 25 µm–1 mm; 0.3–10 THz): in this range (that includes the sub-THz range from 0.3 to 1 THz), there is a gap with respect to semiconductor laser oscillators and to quasiclassical semiconductor oscillators operating at room temperature (or more general: there is a gap with respect to the availability of solid state electronic devices and solid state photonic devices). Quantum cascade lasers working at 80 K cover a part (60–300 µm; 1–5 THz) of the terahertz gap.

28.7 Terahertz Gap

Semiconductor oscillators (Figs. 28.7 and 28.8)—including both laser oscillators and quasiclassical microwave oscillators—are available from the microwave range up to the ultraviolet, however, with the exception of the *terahertz gap*, a frequency range that extends from a sub-THz frequency of about 300 GHz (wavelength 1 mm) to about 30 THz. Cooled quantum cascade lases are partly covering the range of the terahertz gap.

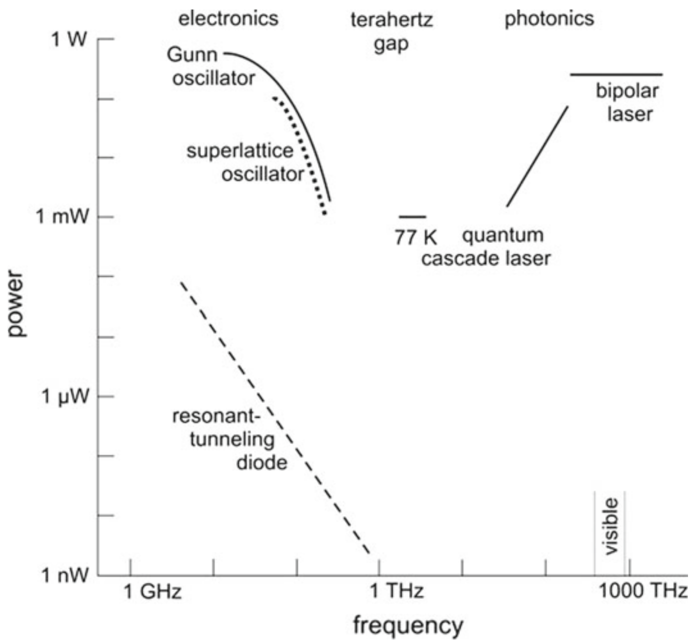

Fig. 28.8 Terahertz gap

Why are room-temperature quantum cascade lasers not available in the range between 4 and 30 THz? There are several reasons: The energy difference $E_2 - E_1$ is of the order of kT or smaller so that the population difference is smaller than at low temperature. Relaxation via phonons is stronger at high temperatures than at low temperatures. If the energy difference $E_2 - E_1$ coincides with the energy of polar optic phonons, relaxation by one-phonon processes occurs, resulting in very short lifetimes of electrons in the upper subband (subband 2); the energy of a polar optic phonon of GaAs is 36 meV (corresponding to a frequency of 8.6 THz).

Another type of unipolar semiconductor laser should be mentioned here, the p germanium laser. This is a unipolar semiconductor laser pumped by a current. It is operated at temperatures below liquid nitrogen temperature. A current pulse applied to a p germanium crystal in a magnetic field gives rise to a nonequilibrium hole population with a population inversion. By feedback with a resonator, laser oscillation occurs. The laser is tunable over a very wide frequency range (0.3–3 THz). Tuning is possible by varying the strength of the magnetic field.

There are, furthermore, CO_2 laser pumped semiconductor lasers emitting far infrared radiation; these have also to be cooled to temperatures below liquid nitrogen temperature. The laser transitions occur between discrete energy levels of impurity ions in semiconductor crystals.

We mention semiconductor oscillators of the range of electronics at frequencies above 100 GHz (*see* Fig. 28.8).

- *Gunn oscillator* (Sect. 31.2). Gunn oscillators are microwave oscillators, commercially available up to about 200 GHz.
- *Semiconductor superlattice oscillator* (Sect. 31.3). Semiconductor superlattice oscillators (up to 200 GHz) are being developed.
- *Resonant tunnel diode oscillator* (Sect. 31.7). Operation of resonant tunnel diode oscillators have been demonstrated up to 700 GHz; however, the output power was very small.

Radiation at frequencies above 100 GHz up to 10 THz can be generated by frequency multiplication of microwave radiation.

Backword wave oscillators are continuous wave oscillators operating in the range from 200 GHz to $\sim$1.5 THz.

References [187–192].

Problems

28.1 Efficiency of bipolar lasers. Compare the efficiency η of different types of GaAs bipolar lasers (double heterostructure laser, quantum wire laser, quantum dot laser, quantum well laser) driven at a current that is ten times larger than the threshold current. Assume, for simplicity, that the quantum efficiency is unity.

28.2 Explain qualitatively why the refractive index in the active regions of a GaAs junction laser is smaller than in the adjacent n-doped GaAs and p-doped GaAs regions.

28.3 Estimate the intensity of luminescence radiation (emitted into the whole space) of the lasers mentioned in Fig. 28.5.