Chapter 11

Semiconductor laser structures
(HL-STRUK)

11.1 Quantum-well laser

In chapter HL we examined essentially semiconductor laser structures with the thickness $d$ of the active region down to approximately $0.1\mu m = 100nm$. In order to achieve, for a given injection rate, a high carrier density, it is useful to reduce the volume as much as possible. Therefore reducing the thickness of the active region down to $d = 5...10 nm$ may be useful. This refers to thicknesses of only about 10-12 atomic layers. Furthermore, such small thicknesses of the active layer are already in the order of the electron wavelength, so that, similar to a dielectric slab waveguide, quantized states are established (These correspond to the eigenmodes of the dielectric slab waveguide). These extremely thin layers are called quantum-wells. In contrast, layers with thicknesses of $d \geq 100nm$ are called 'bulk'-layers. As a result of the state quantization, other amplification characteristics in quantum wells apply. The gain in Fig. 11.1 denotes the gain inside the semiconductor. To determine the gain in the waveguide, the gain has to be multiplied by the fill factor $\Gamma$ (see. page. HL/6).

Though for very thin layers the optical wave guidance is weak, so measures to improve the optical wave guidance are usually necessary. Fig. 11.2 shows on the top the conventional construction of a 'bulk'-active layer (double heterostructure).

In order to achieve an effective optical wave guidance, e.q. a GRIN (graded index) - SQW (single quantum well) structure can be implemented, in which a double heterostructure semiconductor stratification with gradual change in the band gap is achieved by layer-wise change of the semiconductor composition. Thus with thicknesses of $d \leq 10nm$ fill factors of about $\Gamma \approx \text{few}\%$ can be realized.

Due to the limited number of states in a quantum well, the gain of a single quantum well (single quantum well - SQW) is limited. Hence, it is useful to assemble several active layers of quantum wells together (MQW - multiple quantum well). One possible MQW-SCH (SCH - separate confinement heterostructure)-structure is shown in Fig. 11.2. In contrast to 'bulk' active layers, quantum well layers can be strained due to their thinness (where tensions occur due to different lattice constants).
Using a GaAs-substrate with GaAs/GaAlAs cladding layers for example, enables the possibility of creating quantum well of InGaAs, which are used to achieve semiconductor lasers with $\lambda = 980\text{nm}$ (they are used as pump lasers in erbium-doped fiber amplifiers).

Careful adjustment of the strain in quantum wells can significantly reduce the threshold current density. As an example of $\lambda = 1,5\mu\text{m}$-laser with ternary InGaAs- and quaternary InGaAsP-quantum wells, respectively, Fig. 11.3 shows the threshold current density per well, where values below $100\ \text{A/cm}^2$ can be achieved.

With quantum well lasers very low threshold currents can be achieved. Fig. 11.4 shows an example of laser structures and the corresponding optical power-current-diagram with two quantum wells in InGaAs and a GRIN-SCH-structure.

### 11.2 Lateral structuring of semiconductor lasers

The optical wave guidance perpendicular to the active layer was discussed in chapter HL. By appropriate lateral structure of the semiconductor it is ensured, that an optical wave is guided parallel to the active layer. In its simplest form (Fig. 11.5, top left) the lateral structure consists only of a narrow contact strip $w \leq 5\mu\text{m}$ leading to a position-dependent carrier injection into the active layer. Thus a lateral variation of the optical gain $g$ occurs. This can be used to define a lateral waveguide, since the optical wave prefers areas of high optical gain. Such lasers are so-called gain-guided.

Such lasers tend to have instabilities in the optical-power-current diagram (so-called ’kinks’) and have
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Curved phase fronts. Therefore, they have relatively wide lateral far field distributions and can only be coupled poorly into single-mode fibers for example. They also typically show an emission in several longitudinal modes (multi-mode spectrum).

Improved laser emission properties are obtained, if the lateral optical wave guidance features a refractive index variation. Similar to optical fibers this can be achieved by surrounding the central region with materials of smaller refractive indexes. This is called (Fig. 11.5 top right) index-guiding. Such index-guiding semiconductor lasers are expensive to realize, but they show much more stable emission characteristics.

Implementation examples for gain-guided laser are shown in Fig. 11.6, while in Fig. 11.7 examples for index-guided lasers with buried active layer are shown (buried-heterostructure, BH-laser). The lasers based on InP-substrate are generally dimensioned for $\lambda = 1.3...1.65\mu m$, while the lasers based on GaAs-substrate are typically used for $\lambda = 750...850\,nm$ (possibly also for $\lambda = 980\,nm$ with InGaAs-quantum wells). For lasers with a buried active layer, as shown in Fig. 11.7, it is ensured, that the active region is surrounded by material with a lower refractive index. These lasers can have low threshold currents (see e.g. Fig. 11.4), but they are complex to realize due to the necessary multiple epitaxy steps.

A little bit simpler to realize are ‘quasi’-index-guided lasers, as shown in Fig. 11.8, where the active layer is not discontinued. In comparison to Fig. 11.7 these lasers have higher threshold currents. Thus, they are also operable to achieve high optical powers.

11.3 Vertical emitting laser

So far we have discussed only edge-emitting semiconductor lasers, in which the light is emitted from the semiconductor crystal cleaved end face. Unfortunately, these lasers can not be coupled easily to an optical fiber (for efficient light coupling usually a lens is required) and they are, due to the need for a cleaved end face, not on-wafer testable.

Alternatively, vertical emitting lasers can be used. They are also known as VCSEL (vertical cavity surface emitting laser).
Figure 11.3: Achievable threshold current densities in strained quantum wells with compression and tension strains, respectively [P.J.A. Thijs et. al., OFC/IOOC’93]

The basic principle of such a laser is, that the laser oscillation is formed not along the active layer, but perpendicular thereto, as schematically shown in Fig. 11.9. Dielectric mirrors with 4-multiple layers and reflectivities $R_1, R_2$ of about 1 are needed to build-up an oscillation. The build-up oscillation condition (without scattering loss $\alpha_s$) is thus, similar to Eq. 15 (HL/10), given by:

$$\exp(2g_{st}d) = 1/(R_1 \cdot R_2)$$

(11.1)

and for $g_{st} \cdot d << 1$, respectively, by

$$2g_{st}d = 1 - R_1 \cdot R_2$$

(11.2)

Quantum wells are customary use for VCSELs, wherein, for example, a gain of $g_{st} = 6000/cm$ is necessary for $R_1 = 99\%$, $R_2 = 99, 8\%$, $d = 10nm$. Such a gain is still feasible, hence VCSELs can be realized in this structure. A specific embodiment is shown in Fig. 11.10, where the mirrors are realized by a $\frac{3}{4}$-GaAs/$\frac{1}{4}$-(Ga)AlAs-stratification, which matches the lattice of the GaAs-substrate. A breakthrough has yet only been achieved for VCSELs based on GaAs-substrate and mirrors with multiple layer pairs of Ga(Al)As/(Ga)AlAs. With active regions of Ga(Al)As with the wavelength $\lambda \leq 850nm$ and with strained InGaAs quantum well layers, wavelengths of up to $\lambda \approx 1\mu m$ can be achieved. High efficient laser with low threshold currents can be realized. Fig. 11.11 shows a VCSEL for $\lambda \approx 970nm$ with a spot diameter of 7$\mu m$, that has a threshold current of only $I_s = 0.35mA$. On the other hand, efficiencies over $> 50\%$ ($\approx$ [optical power]/[electrical power]) can be achieved with a current of only 2 mA leading to a high-efficient light source.
Figure 11.4: Laser structure (4a) and Optical power over current diagram (4b) of a laser with 2 InGaAs-quantum wells [T.R. Chen et. al., Appl. Phys. Lett., 60(1992), p. 1782]
Figure 11.5: Characteristics of gain-guided and index-guided semiconductor lasers [S. Hansmann, Laserdioden, from: Voges, Petermann; Handbuch der Optischen Kommunikationstechnik, Springer, 2002]

Figure 11.6: Gain-guided laser [S. Hansmann, Laserdioden, from: Voges, Petermann; Handbuch der Optischen Kommunikationstechnik, Springer, 2002]
Figure 11.7: Index-guided lasers with a buried active layer [S. Hansmann, Laserdioden, from: Voges, Petermann; Handbuch der Optischen Kommunikationstechnik, Springer, 2002]

Figure 11.8: Quasi-index-guided lasers with a ridge active layer [S. Hansmann, Laserdioden, from: Voges, Petermann; Handbuch der Optischen Kommunikationstechnik, Springer, 2002]

Figure 11.9: Schematic of a vertical emitting semiconductor laser with the active layer of thickness $d$ and the mirror reflectivities $R_1, R_2$
Figure 11.10: Principal Structure of a VCSEL (left) and realization of two dimensional VCSEL-arrays (right) [K.J. Ebeling, Laserdioden mit Vertikalresonator (VCSELs) für optische Verbindungssysteme, from: Voges, Petermann; Handbuch der Optischen Kommunikationstechnik, Springer, 2002]

Figure 11.11: Optical power-current and voltage-current diagram for a VCSEL with a 7μm diameter for λ = 970 nm [K.L. Lear et. al., Electron. Lett., (31)1995, p. 208]