

# Chapter 24

## Quantum Well Lasers from the UV to the Infrared

Quantum well lasers are available in a large wavelength range, extending from the near UV to the near infrared. Basic materials are: GaN for UV and blue lasers; GaAs for red lasers; InP for near infrared lasers; GaN, GaAs or ZnSe for green lasers. We will discuss the design of different lasers.

### 24.1 A Survey

Figure 24.1 shows a selection of quantum well materials, together with barrier and substrate materials. At each wavelength in the range of 0.3–2  $\mu\text{m}$ , a laser diode is in principle available. The materials used for preparing a laser diode must have appropriate energy gaps. There are further requirements.

- *Red and infrared laser diodes.* The materials must have a very good lattice matching. This condition requires the use of binary, ternary and quaternary compounds. Suitable substrates are GaAs and InP. Heterostructures are prepared by molecular beam epitaxy.
- *Blue and UV laser diodes.* The material basis is GaN. The lattice matching is not critical. Sapphire has a large lattice mismatch to GaN, but it is nevertheless suitable as a suited. Heterostructures can be prepared by chemical vapor deposition (CVD).
- *Green laser diodes.* The basic materials are GaN, GaAs, or ZnSe.

### 24.2 Red and Infrared Laser Diodes

By mixing GaAs with the heavier InAs, all energy gaps between the gap of GaAs (1.4 eV) and the gap of InAs (0.4 eV) are available (Fig. 24.2a). All ternary  $\text{Ga}_{1-x}\text{In}_x\text{As}$  ( $x = 0 \dots 1$ ) compounds are direct semiconductors. InP is an appropriate substrate material. As a rule of determination of a property  $a$  (like gap energy or

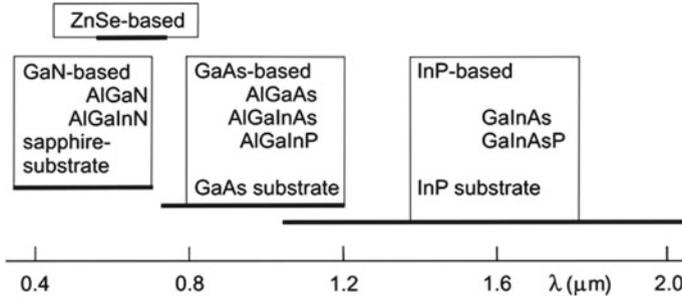


Fig. 24.1 Quantum well lasers: materials and wavelength regions

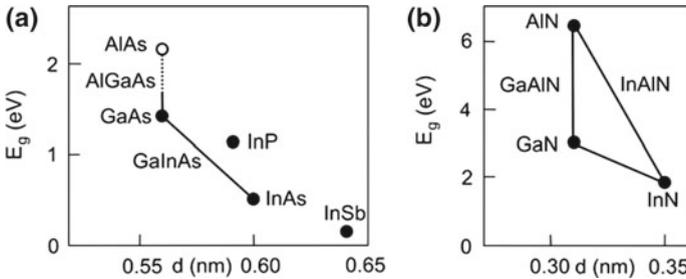


Fig. 24.2 Energy gaps **a** of GaAs-based and **b** of GaN-based semiconductors

lattice constant) of a semiconductor consisting of the compounds A, B, and C, we can use the relation  $a(A_{1-x}B_xC) = (1 - x) \times a(AC) + x \times a(BC)$ .

*The following materials are lattice matched to InP.*

- InP and  $Ga_{0.52}In_{0.48}As$  (a combination of a binary and a ternary semiconductor). The energy gap of  $Ga_{0.52}In_{0.48}As$  has the value  $E_g = 0.75$  eV and the refractive index is  $n = 3.56$  while the refractive index of InP is  $n = 3.16$  at the gap energy (1.2 eV) of InP.
- InP and  $Ga_{1-x}In_xAs_{1-y}P_y$  (a combination of a binary and a quaternary III–V compound); Ga is partly replaced by the heavier In and As by the lighter P.

These materials, together with InP substrates, are suitable for the preparation of a variety of lasers.

- $Ga_{1-x}In_xAs/GaAs$  laser; wavelength in the range 900–1100 nm; application: pump lasers.
- $Ga_{0.8}In_{0.2}As/GaAs$ ; 980 nm; application: pump laser of the  $Er^{3+}$ : glass fiber laser and amplifier.
- $Ga_{1-x}In_xAs_{1-y}P_y/GaInAsP$ ; 1.2–1.6  $\mu m$ .
- $GaInAs/GaInAlAs$ ; 1.8–2.1  $\mu m$ .

The following materials, lattice matched to InP, are suited to prepare lasers used in optical communications.

- $\lambda = 1.32 \mu\text{m}$ ;  $\text{Ga}_{0.27}\text{In}_{0.73}\text{As}_{0.58}\text{P}_{0.42}$ .
- $\lambda = 1.55 \mu\text{m}$ ;  $\text{Ga}_{0.42}\text{In}_{0.58}\text{As}_{0.9}\text{P}_{0.1}$ .

*Lasers with GaAs substrates.*

- GaInP (quantum layer)/AlGaInP; wavelength  $\lambda \sim 630\text{--}700\text{nm}$ ; pump laser of other lasers.
- $\text{Ga}_{1-x}\text{Al}_x\text{As}/\text{Ga}_{1-y}\text{Al}_y\text{As}$ ;  $720\text{--}850\text{nm}$ ; pump lasers.

### 24.3 Blue and UV Laser Diodes

In 1997, S. Nakamura and coworkers at a small Japanese company (Nichia Chemicals) succeeded in preparing blue diode lasers [196, 203, 204]. In 2014, Nakamura received, together with H. Amano and I. Akasaki, the Nobel Prize in Physics. The basic materials are nitrides (Fig. 24.2b), belonging to the group III–V semiconductors:

- GaN;  $E_g = 3.4 \text{ eV}$  ( $\lambda_g = 365 \text{ nm}$ ).
- AlN;  $E_g = 6.2 \text{ eV}$ .
- InN;  $E_g = 1.8 \text{ eV}$ .

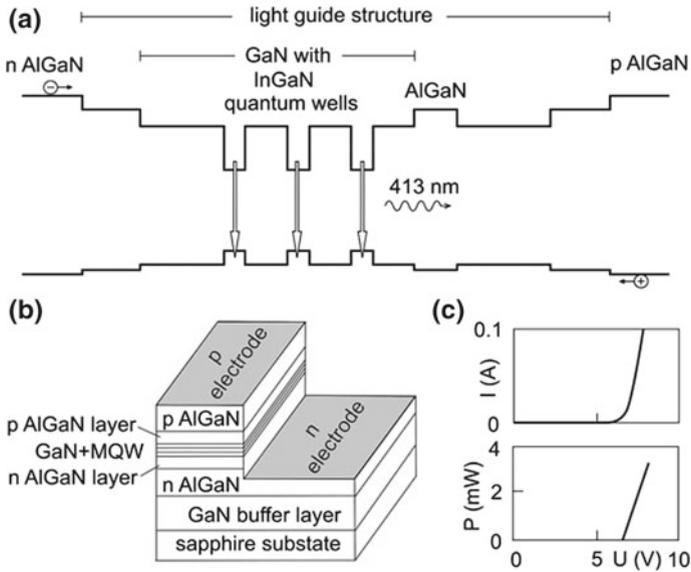
$\text{Ga}_{1-x}\text{Al}_x\text{N}$  and  $\text{Ga}_{1-x}\text{In}_x\text{N}$  mixed materials are most suitable for preparation of blue and near UV laser diodes. Although sapphire ( $\text{Al}_2\text{O}_3$ ) has a large mismatch (16%) to GaN, it serves as a substrate; SiC is suitable as substrate too.

An example of a GaN-based laser diode is shown in Fig. 24.3a. The laser diode (emitting at a wavelength of 413 nm) consists of the following layers.

- InGaN quantum well layers (thicknesses 3 nm).
- GaN barrier layers.
- GaAlN (p type) electron blocking layer; it acts as a reflector of electrons.
- GaAlN layers, n-doped on one side and p-doped on the other side of the GaN layer.

At a wavelength of 400 nm, the refractive index of GaN is  $n = 2.55$ , while the refractive index of AlGaIn is smaller. Doping with silicon leads to n-type conductivity and doping with magnesium to p-type conductivity.

The design of a blue laser diode is shown in Fig. 24.3b. The different layers are (beginning at the  $\text{Al}_2\text{O}_3$  substrate): a very thin undoped GaN layer (e.g., of a thickness of 50 nm) as buffer layer; an n-doped AlGaIn cladding layer; then the layers embedding the layers containing the multi-quantum wells (MQWs); finally, a p-doped AlGaIn cladding layer. The pump current flows from the metallic anode through the heterostructure to the metallic cathode.



**Fig. 24.3** Blue laser diode. **a** Principle. **b** Design. **c** Dependence of the current and the laser output power on the voltage across the diode

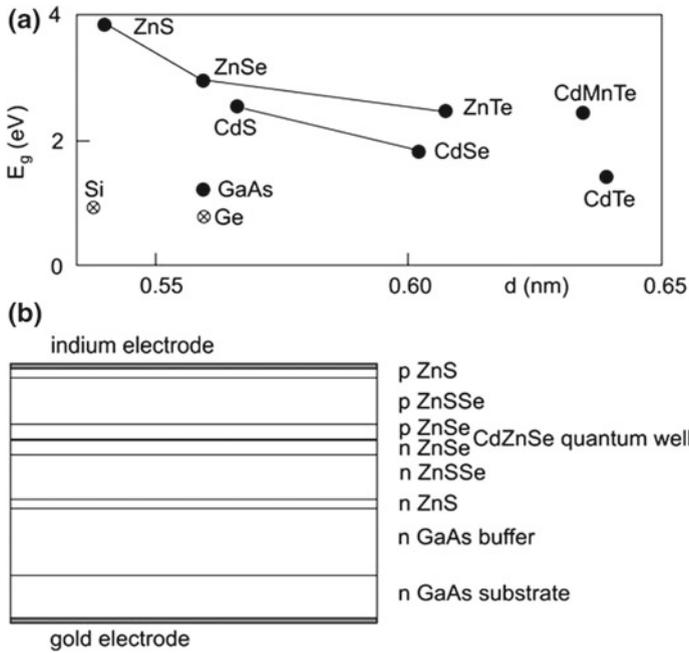
The current-voltage ( $I$ - $V$ ) curve (Fig. 24.3c) shows that current flow sets in at a voltage above 5 V. At a voltage of 7 V, the threshold current  $I_{th}$  is reached. In the range  $I > I_{th}$ , the current increases strongly due to generation of laser radiation. The laser output power  $P_{out}$  increases almost proportionally to  $I - I_{th}$ .

## 24.4 Group II-VI Materials of Green Lasers

As already mentioned, green laser diodes consist of GaAs-, GaN- or ZnSe-based materials. The ZnSe-based mixed materials have energy gaps between 2 and 4 eV (Fig. 24.4a). There are various possibilities to prepare mixed crystal materials composed of elements of group II and group VI in the periodic table.

- *Binary II-VI semiconductors*: ZnS, ZnSe, CdSe ....
- *Ternary II-VI semiconductors*: ZnSSe, ZnSeTe, CdSSe, CdZnSe with energy gaps between 3.8 eV (ZnS) and 1.8 eV (CdSe); lattice matched to GaAs (substrate).

The layer sequence of a ZnS-based laser diode [205, 206] is shown in Fig. 24.4b. On an n-doped GaAs substrate, first a GaAs buffer layer is grown in order to obtain a perfect crystal structure to which the further layers are added. The different tasks of the layers are as follows:



**Fig. 24.4** Green semiconductor laser. **a** Energy gaps. **b** Device

- CdZnSe (quantum well).
- p ZnSSe/p ZnSe/CdZnSe/ n ZnSe/ n ZnSSe (light guide).
- p-doped layers (hole injector).
- n-doped layers; electron injector.
- An indium film on the heterostructure serves as anode and a gold film on the backside of the highly doped substrate as cathode.

Heterostructures of group II–VI semiconductors are not as stable as those of group III–V semiconductors.

### 24.5 Applications of Semiconductor Lasers

We mention a few applications of semiconductor lasers: optical storage (e.g., compact disc; blue ray disc); color projection; laser printer; sensor devices; micro controllers. In comparison with a red laser, a blue laser emits radiation of smaller wavelength. Therefore, a blue laser allows for a higher storage density.

References [1–4, 6, 187–201, 203–206].

## Problems

**24.1 GaN quantum well.** The effective mass of ( $m^* \sim 0.2 m_0$ ) of conduction electrons in GaN is about three times the effective mass of conduction electrons in GaAs.

- (a) Compare the density of states of electrons in a GaN quantum well with the density of states of electrons in a GaAs quantum well.
- (b) Compare the condition of gain mediated by a GaN quantum well with the condition of gain mediated by a GaAs quantum well.