Chapter 1

Introduction

Laser diodes are fascinating devices: tiny chips, much smaller than a cubic millimeter, which extremely efficiently convert electrical power in laser light. Depending on the semiconductor crystal composition, their emission wavelength can be almost freely customized over a broad spectral range. Laser diodes have been part of our everyday life for the last twenty years, at least since the first CD players entered our homes, or the first hand-held barcode scanners were installed in our supermarkets. A picture of laser diode chips fabricated in this work is shown in Fig. 1.1.

In this introductory chapter, the current state of the art of GaN-based laser diodes and their applications will be briefly introduced (section 1.1). The basic principles of semiconductor lasers will be then illustrated in section 1.2. Finally, an overview of the topics discussed in this PhD thesis will be given in section 1.3.

Figure 1.1: GaN-based laser diode chips of variable resonator length on millimeter paper. The resonator lengths are, from right to left, 600 μm, 800 μm, 1000 μm, 1200 μm. The width of the chips is 400 μm, their thickness 200 μm. The electrical contacts are the metalized top and bottom surfaces (©FBH/schurian.com).

1.1 State of the art and applications of GaN-based laser diodes

The first laser diodes (LDs) were fabricated on gallium arsenide in 1962. GaAs has a bandgap energy of around 1.4 eV, so that its emission wavelength is in the near-infrared region (ca. 867 nm). By combining GaAs with other III-V semiconductor alloys, (Al,Ga,In)(As,P)-based laser diodes emitting in the near-infrared and red regions of the spectrum (ca. 1900 nm–630 nm) could be demonstrated [1]. Typically, laser diodes emitting in these regions are fabricated on GaAs, more seldom InP, substrates. In Fig. 1.2 the most common compound semiconductors, their bandgaps and their lattice constants are shown.

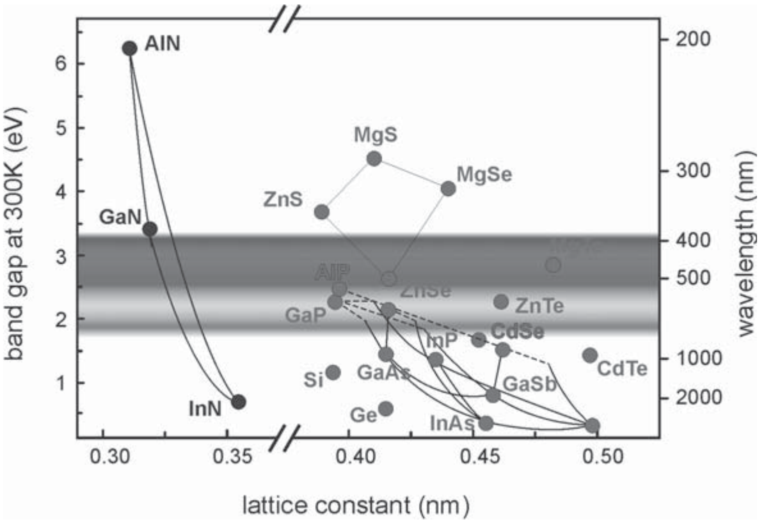


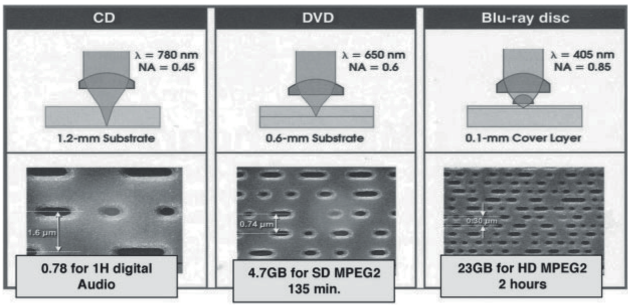
Figure 1.2: Bandgap vs lattice constant for the most common compound semiconductors (sources: [2] [3]).

The fabrication of efficient laser diodes emitting at short wavelengths, i.e. covering the blue and green regions of the visible spectrum, was more challenging. II-VI materials of the (Zn,Mg)(S,Se) family, which can be grown lattice-matched to GaAs, were investigated first. However, the issues of very short device lifetime and lack of reliability typical for laser diodes fabricated on these materials could never be fully solved [4]. The decisive breakthroughs came in the late 80's, when good-quality p-doped GaN crystals could be realized [5]. This paved the way for the fabrication of blue-violet high-brilliance LEDs (1993) and laser diodes (1996), based on the (In,Al,Ga)N material system [6].

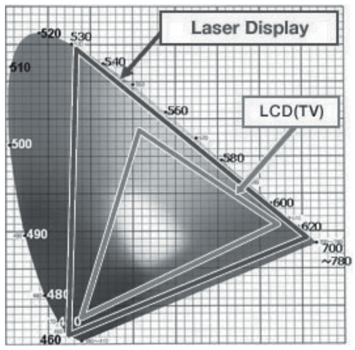
(In,Al,Ga)N laser diodes were first fabricated on sapphire and silicon carbide substrates, but today freestanding GaN wafers are available. The GaN bandgap energy of 3.4 eV corresponds to light emission in the near-UV region, at 365 nm. Since the growth of good-quality lattice-matched quaternary alloys is difficult, InGaN quantum wells (QWs) are usually grown to obtain visible violet and blue emission. Where a larger bandgap is needed, as in the cladding layers, AlGaN is used. Since InGaN and AlGaN are not lattice-matched to the substrate, large mechanical stress is induced in the epitaxial layers. Besides, although (Al,In,Ga)N-based devices can theoretically cover a very broad wavelength spectrum, from the infrared (InN) to the UV (AlN), shifting the emission wavelength is challenging, among other reasons, because the lattice mismatch to the substrates is enhanced.

Today, blue-violet GaN-based laser diodes have entered our homes as part of the most recent optical data storage system: the *Blu-Ray Disc*. In Blu-Ray players, a 405 nm-laser diode is used. Thanks to the shorter wavelength, if compared to the red laser diode in DVD systems (650 nm), the spot-size is reduced, and the data density increased (cf. Fig. 1.3 (a)) [7]. Many other applications are emerging, which exploit the reduced spot-size of blue-violet laser diodes. Among them, laser printing and laser photolithography are worth mentioning [7].

Another emerging mass-market for (Al,In,Ga)N devices are laser-based RGB projectors [8, 9]. Due to the high spectral purity of laser light, laser projection offers very bright color rendering, as illustrated in Fig. 1.3 (b). Efficient (Al,Ga,In)P red laser diodes are already available. As soon as direct green and blue LDs of comparable quality will be available as well, which is expected to happen in the next years, the fabrication of extremely small and efficient portable *pico-projectors* will be possible.



(a) spot size comparison of CDs, DVDs, and Blu-Ray Discs [7]



(b) color gamut of laser display compared to LCD [10]

Figure 1.3: In (a) the spot size of CDs, DVDs, and Blu-Ray Discs is compared . In (b) the color gamut achievable with a laser display is compared to a common LCD color gamut.

The research presented in this thesis is focused on the development of lateral-single-mode, narrow-linewidth laser diodes emitting in the blue-violet region of the spectrum (roughly 400 nm to 450 nm). This kind of devices finds application especially in the field of spectroscopy, where a precisely tunable wavelength, but limited emission powers are needed.

Prior to this work, laser diodes on sapphire and on GaN substrate had already been demonstrated at the Ferdinand-Braun-Institut (FBH), using a fabrication process transferred from GaAs. During this work, the process technology was developed, in order to fabricate vertical-injection devices suitable for standard packaging and continuous-wave (CW) operation. Several process steps were systematically investigated and optimized, with the goal of obtaining a reliable and reproducible process. Besides, several aspects concerning the physics of the devices were studied using the fabricated devices.

1.2 Basic principles of laser diodes

In this section, the fundamentals of laser diodes will be briefly introduced. For a more detailed discussion on the physics of laser diodes in general, and of GaN-based and narrow-linewidth laser systems in particular, a rich literature is available [1, 6, 11–13].

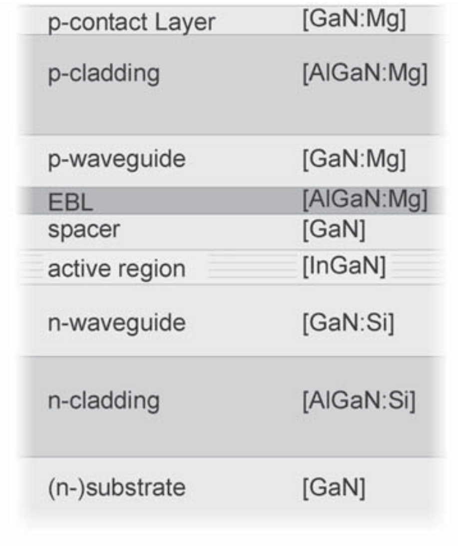
In laser diodes, the population inversion necessary for lasing is achieved by means of a *double heterostructure*. In the most simple case, it consists of three semiconductor layers, where a narrower-bandgap layer is sandwiched between two wider-bandgap *cladding layers*. Usually, the top layer is p-doped and the bottom one n-doped, so that the charge carriers (holes and electrons) can be injected in the undoped middle layer by applying an external electrical field. Due to the bandgap difference, the carriers are trapped in the middle layer, so that large carrier densities can be achieved. If the thickness of the sandwiched layer is reduced to a few nanometers, quantum effects occur, and the layer becomes a *quantum well* (QW).

At sufficiently high carrier injection, the stimulated emission in the QW exceeds absorption, and the light is amplified. By adding two opposing mirrors which form a Fabry-Perot cavity around the gain medium, lasing can be achieved. The mirrors are usually obtained by controlled cleaving of the semiconductor crystal, in such a way that, ideally, the facets are atomically flat.

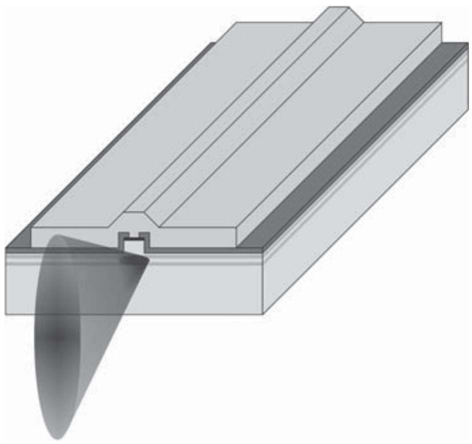
Not only the charge carriers but the emitted light, too, is confined in vertical direction in order to maximize the light amplification. Two additional *waveguiding layers* with an intermediate bandgap are typically inserted between the QW and the cladding layers. Due to the refractive index difference which follows from the bandgap difference, they confine the optical mode in vertical direction. Laser diodes are typically designed for vertical-single-mode operation. Laterally, single-mode or multi-mode emission can be achieved, depending on the strength of the confinement and the width of the emitting stripe. In this work, the focus will be on lateral-single mode devices where the lateral confinement of light is obtained by etching a ridge-waveguide in the semiconductor surface. The current path is confined in lateral direction, as well, by placing the p-contact on top of the ridge. In longitudinal direction, usually several modes oscillate in parallel, which are determined by the allowed Fabry-Perot modes and the material gain spectrum. Longitudinal single-mode emission, hence narrow linewidth, can be achieved by implementing a mode selection mechanism such as a Bragg grating in the laser.

Obviously, a real epitaxial structure is more complex than described above. A typical GaN laser diode may have several QWs separated by quantum barriers, and an *electron blocking layer* is typically placed in the p-side to increase the carrier injection efficiency. A realistic epitaxial structure is shown in Fig. 1.4 (a). The devices discussed in this work are grown by metalorganic vapor phase epitaxy (MOVPE, also known as metalorganic chemical vapor deposition or MOCVD), which is the most common growth method for GaN laser diodes. As substrates, in this work mostly bulk GaN substrates are used. However, sapphire wafers were common until a few years ago, and are still used for test purposes.

(In,Al,Ga)N crystals are grown in the wurtzite crystal structure. This fact, together with the stress in the epitaxial layers, results in strong internal polarization fields which have a great influence on the device properties. Because of the anisotropy of the crystal structure, different surfaces of the crystal have very different properties: in this work *c-plane* wafers will be used, which have an in-plane hexagonal symmetry and strong polarization fields perpendicular to the surface. The fabrication of devices on alternative crystal orientations is currently under investigation at the *Ferdinand-Braun-Institut* (FBH) and the *Technische Universität Berlin* (TUB) [14] [15], but will not be discussed here.



(a)



(b)

Figure 1.4: (a) typical epitaxial structure of a GaN laser diode and (b) schematic of a finished device.

1.3 Structure of this PhD thesis

The front-end fabrication process for narrow-ridge laser diodes on GaN substrate will be investigated in chapter 2. Although a mature and reliable fabrication process for laser diodes on GaAs is available at the FBH, obtaining a reliable and reproducible process on GaN is not trivial. Commercially available GaN substrates are not comparable in size, flatness and surface topology to their GaAs counterparts. This makes the precise definition of narrow ridge waveguides, as necessary for lateral-single-mode operation, very difficult. Moreover, the different chemical, mechanical and electrical properties of GaAs and GaN require the development of new technologies and, for instance, new contact metal systems. In particular, the fabrication of n-contacts on the backside surface of the substrate will be discussed.

In chapter 3 the back-end processing will be studied. The fabrication of smooth facets will be the main topic: the issues correlated to wafer thinning, laser scribing, diamond scribing and facet cleaving will be studied. Since this work is focused on the fabrication of devices with narrow-linewidth emission, anti-reflection coatings will be studied. These are necessary to suppress the Fabry-Perot modes, when optical feedback is provided by an optical grating. The dependence of the device performance on the facet reflectivity will be studied with a simple analytical model.

In chapter 4, a more in-depth analysis of certain aspects of the device physics will be presented. In particular, the mode behavior will be studied with different simulation methods, in order to understand the influence of the ridge-waveguide etch depth on the lasing performance. A self-consistent simulation software will be used to investigate the role of current spreading and index-antiguiding; the effects of antiguiding will be then studied more in detail with a 2D mode solver. Advanced characterization methods will be used to confirm the simulation results. Among other parameters, the antiguiding factor will be determined.

The subject of longitudinal mode selection will be the discussed in chapter 5. Two approaches will be considered: an external cavity diode laser (ECDL) system will be realized by an industrial partner combining FBH-fabricated laser diodes with a commercially available diffraction grating. A feasibility study for a distributed feedback (DFB) laser diode, including discussion of the design and development of suitable lithography and etching process will be presented.

The presented results will be summarized, and an outlook on future research will be given in chapter 6.

Chapter 2

Front-end processing of GaN-based laser diodes

With the term *processing*, all the laser diode fabrication steps following epitaxial growth, which lead from the blank wafer to the finished device, are indicated. The first part of the processing, including all fabrication steps from the first wafer surface cleaning to substrate thinning, will be referred to as *front-end-of-the-line* (FEOL), or simply *front-end*. Front-end processing is performed in strict clean-room environment (class ISO 6 or higher)[1] and involves steps like photolithography, thin-film deposition techniques, dry and wet-chemical etching. The *back-end-of-the-line* (BEOL or *back-end*) follows, in which the substrate is thinned, separated to single devices (*dicing*) and packaged. During back-end, other steps like facet coating (in the case of laser diodes) and backside contact deposition may also be performed. The clean-room requirements are more relaxed in the back-end stage (ISO class 8).[2]

In this chapter the front-end fabrication process of GaN laser diodes will be discussed. Generally speaking, the most simple laser diode design consists of two metal contacts, deposited on the n-doped and p-doped semiconductor surfaces, and of a Fabry-Perot resonator, with parallel mirrors formed by the cleaved semiconductor facets. Additionally, the optical mode(s) and the current injection are laterally confined in a defined manner. According to the optical confinement technique implemented, laser diodes can be classified in gain-guided or index-guided devices [1].

A fabrication process for broad-area, gain-guided laser diodes (BA-LDs) was developed. This very simple process, with a single lithography step, will be briefly discussed in section 2.2. The devices fabricated in this way allow quick qualification of the epitaxial wafer, however, they are not suitable for packaging and CW operation, and they are lateral-multi-mode.

To obtain lateral single-mode operation, a sufficiently large lateral confinement of the optical mode(s) in a narrow space is needed, which can be obtained only by index guiding. The most

[1] class ISO 6, defined according to the ISO 14644-1 cleanroom standards, is equivalent to class 1000 in the US Federal Standard 209E.

[2] class ISO 8 corresponds to class 100 000 in the US FED STD 209E.

straightforward way to obtain lateral index guiding is to etch a ridge waveguide (RW) in the semiconductor surface and to place the p-contact on top of it. Since the focus of this work is on lateral-single-mode laser diodes, in this chapter mainly the processing of such kind of devices, i.e. ridge-waveguide laser diodes (RW-LDs), will be studied. In section 2.3 an overview of the RW-process will be given; the definition of insulated ridge waveguides will be discussed in section 2.4. Finally, the development ohmic backside n-contacts will be discussed in section 2.5.

2.1 Technology roadmap

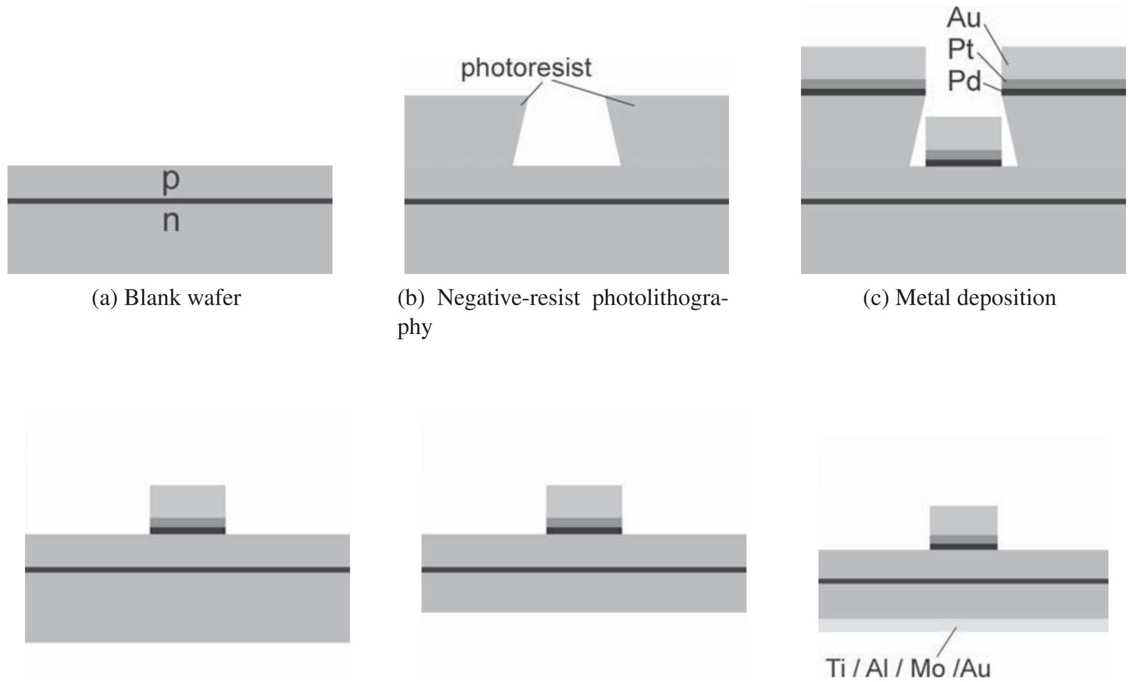
Before this work was started, a fabrication process for ridge-waveguide, GaN-based laser diodes on sapphire substrates was already available at the FBH. Applying the same fabrication steps on GaN substrates, devices capable of CW operation could also be demonstrated. The device concept, however, was not optimal, particularly in terms of packaging. Both p and n-contacts were placed on the wafer epi-side, corresponding to a lateral device: while this is necessary when electrically non-conductive sapphire substrates are used, on GaN substrates a vertical device is more convenient. In order to allow vertical current injection, n-contacts suitable for the wafer backside were studied as part of this work (see section 2.5). Issues linked to packaging were also tackled, as it will be discussed in chapter 3, section 3.4. Other improvements of the fabrication process included the introduction of Pd metal contacts, which triggered an in-depth investigation of the ridge patterning technology, as discussed in sections 2.4.2 through 2.4.5.

The reduction of the wafer size, from full 2-inch wafers to 2-inch-wafer quarters, was another significant change in process technology introduced during this work. As it will be explained in more detail later, the fragility of the GaN substrates leads to frequent wafer breaking during processing. Reducing the wafer size helps reducing the risk of breaking, thus considerably increases the yield. For the same reason, contact lithography is preferred over projection lithography, since it is more flexible and allows processing of wafers of non-conventional shape and size. The development of a contact lithography process will be the subject of section 2.4.1.

2.2 The quick broad area fabrication process

The simple fabrication process for BA-LDs, or BA-process, is illustrated in Fig. 2.1. After thermal p-doping activation [16] in a rapid thermal annealing (RTA) unit, a metal stripe is defined on the semiconductor surface. This step is performed through negative photoresist lithography and metal lift-off. A 1 µm-thick metal stack of Pd/Pt/Au is used; annealing in an RTA unit follows. Pd is chosen as a contact metal because of its high work function, which makes it suitable as a contact to p-doped, large-bandgap semiconductors such as GaN [17]. The role of the overlying Pt and Au layers is only mechanical reinforcement of the contacts.

It should be noted here that, if the goal was to obtain the lowest possible p-contact resistances, this would not be the optimal approach. As it will be explained in the following, lower contact resistivity can be achieved by first depositing a single Pd layer, then proceed to RTA annealing and metal reinforcement. This would however require an additional lithography step, which would significantly



(a) Blank wafer

(b) Negative-resist photolithography

(c) Metal deposition

(d) Lift-off and annealing

(e) Wafer thinning

(f) Backside n-contact deposition

Figure 2.1: Illustration of the main processing steps for the quick fabrication of simple gain-guided, broad area laser diodes.

increase the process duration. In the BA-process, since the main goal is *quick* characterization of the epitaxial wafer, slightly higher contact resistances are accepted in order to speed up the process. After annealing, the front-end process is finished. The wafer is then thinned and an Al-based contact is deposited on its backside. Facet cleaving follows. These back-end processing steps are mostly the same as in the ridge waveguide fabrication process and will be discussed in detail in chapter 3.

The BA-process has the advantages of being quick and robust, it is however not suitable for the fabrication of lateral single-mode laser diodes. As already pointed out, to obtain lateral single-mode operation, narrow RW-LDs are needed. The presented process for the fabrication of gain-guided LDs has been developed, and is still in use, at the Ferdinand-Braun-Institut (FBH). It allows quick fabrication of multi-mode, broad-area laser diodes (BA-LDs), with the sole goal of epitaxy qualification. Such gain-guided BA-LDs are not suitable either for packaging nor for CW operation. Measurement data obtained from a laser diode fabricated with the presented BA-process on an FBH-grown epiwafer are shown in Fig. 2.2.

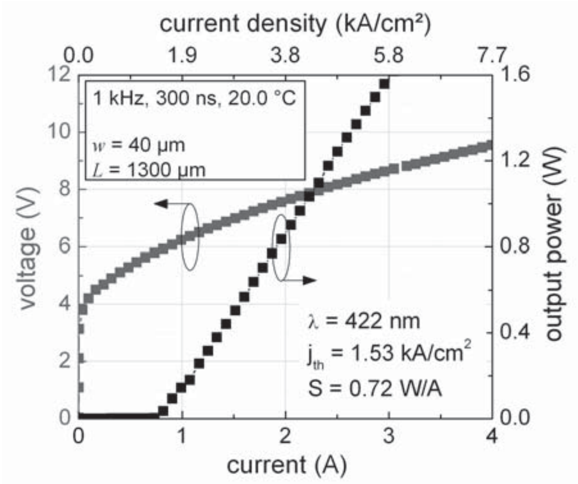


Figure 2.2: L–I and V–I characteristics of an InGaN MQW broad-area laser diode (BA-LD) grown, processed, and measured in pulsed operation at the FBH. The facets are uncoated.

2.3 The ridge-waveguide process – an overview

In this section only a brief overview of the fabrication process for RW-LDs (RW-process) will be provided. A detailed discussion of the most important process steps will follow, according to the sequence of the process steps. An overview of the whole process is given in the schematic in Fig. 2.3.

The first step, after p-doping activation, is the deposition of Pd as the p-contact, then the ridge waveguide is etched in the metal and the semiconductor surface. Following ridge patterning the whole surface is coated with an electrically insulating layer, which is then selectively removed on top of the ridge using lithography and etching. The many issues correlated to the definition of narrow ridge-waveguides will be presented in section 2.4. Following the insulator patterning large metal pads are deposited, which not only provide the electrical contact to the Pd layer through the insulator opening, but also play an important role in heat dissipation during CW operation. Thinning of the substrate follows, then the backside n-contacts are deposited (cf. section 2.5). Not shown in the process flow are the last back-end process steps, i.e. facet cleaving and coating, dicing, and mounting on heatsink, which will be discussed in chapter 3, together with substrate thinning.