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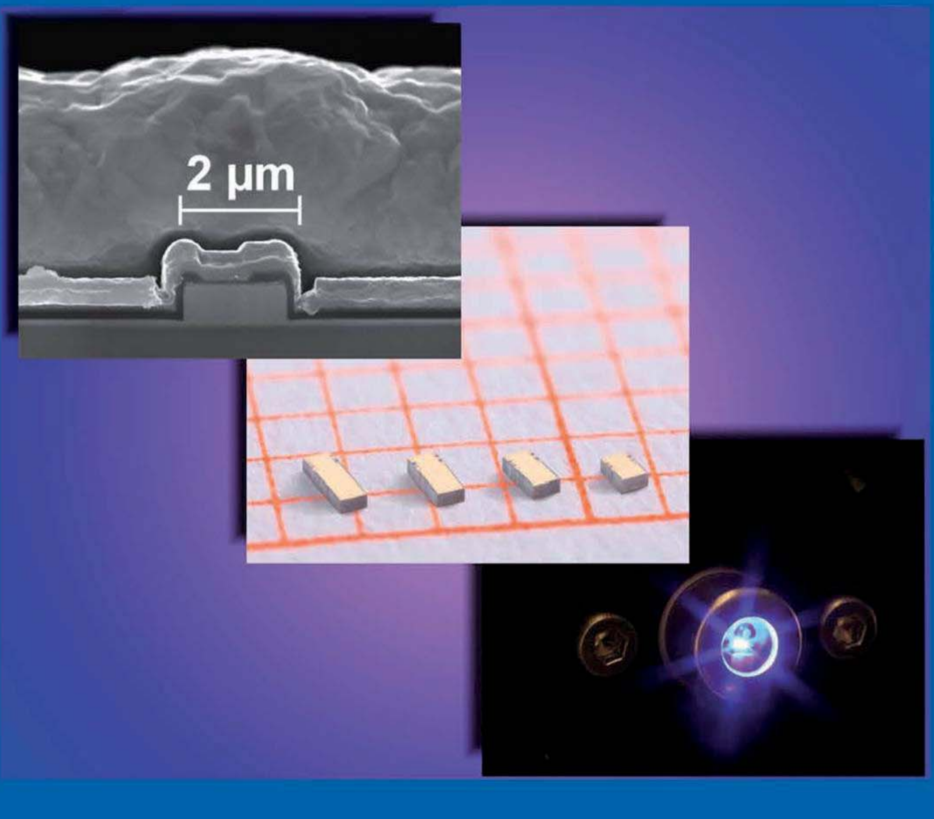
Innovationen mit Mikrowellen & Licht

Design and fabrication of GaN-based laser diodes for single-mode and narrow-linewidth applications



Luca Redaelli

aus der Reihe:

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Design and fabrication of GaN-based laser diodes for single-mode and narrow-linewidth applications

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Innovations with Microwaves and Light

Research Reports from the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik

Preface of the Editors

Research-based ideas, developments, and concepts are the basis of scientific progress and competitiveness, expanding human knowledge and being expressed technologically as inventions. The resulting innovative products and services eventually find their way into public life.

Accordingly, the *“Research Reports from the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik”* series compile the institute’s latest research and developments. We would like to make our results broadly accessible and to stimulate further discussions, not least to enable as many of our developments as possible to enhance everyday life.

To make GaN-based laser diodes usable for applications like spectroscopy it is indispensable that they stably emit light at defined wavelengths in the violet and blue spectral region. How to obtain the corresponding ridge waveguide laser diodes with low threshold, high efficiency, and optimum beam shape, as well as various technological and physical aspects of the chip fabrication process are studied in this report. For instance, the strong impact of the ridge etch depth on the lasing threshold and the far field pattern could be attributed to a pronounced index-antiguiding which reduces the lateral optical confinement of the lasing mode. After coping with various challenges in chip processing, external cavity diode laser which operate in continuous mode and are tuneable over several nanometers were successfully demonstrated in collaboration with an industrial partner.

We wish you an informative and inspiring reading

Günther Tränkle
Prof. Dr. Günther Tränkle
Director

Wolfgang Heinrich
Prof. Dr.-Ing. Wolfgang Heinrich
Deputy Director

The Ferdinand-Braun-Institut

The Ferdinand-Braun-Institut researches electronic and optical components, modules and systems based on compound semiconductors. These devices are key enablers that address the needs of today’s society in fields like communications, energy, health and mobility. Specifically, FBH develops light sources from the visible to the ultra-violet spectral range: high-power diode lasers with excellent beam quality, UV light sources and hybrid laser systems. Applications range from medical technology, high-precision metrology and sensors to optical communications in space. In the field of microwaves, FBH develops high-efficiency multi-functional power amplifiers and millimeter wave frontends targeting energy-efficient mobile communications as well as car safety systems. In addition, compact atmospheric microwave plasma sources that operate with economic low-voltage drivers are fabricated for use in a variety of applications, such as the treatment of skin diseases.

The FBH is a competence center for III-V compound semiconductors and has a strong international reputation. FBH competence covers the full range of capabilities, from design to fabrication to device characterization.

In close cooperation with industry, its research results lead to cutting-edge products. The institute also successfully turns innovative product ideas into spin-off companies. Thus, working in strategic partnerships with industry, FBH assures Germany’s technological excellence in microwave and optoelectronic research.

Design and fabrication of GaN-based laser diodes for single-mode and narrow-linewidth applications

vorgelegt von
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zur Erlangung des akademischen Grades

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Abstract

In this work, several aspects concerning (In,Al,Ga)N laser diodes with high spectral purity, designed for applications in spectroscopy, were studied. A fabrication process for the definition of narrow ridges on the wafer surface was investigated. In GaN devices, ridge-waveguide widths below 2 µm are typically needed in order to achieve lateral-single-mode lasing, which is challenging on currently available GaN epitaxial wafers. Besides investigating the standard technologies, a self-aligning approach was proposed. The fabrication of ohmic n-contacts on the nitrogen-polar wafer backside was studied as well. Specific resistances below $1 \times 10^{-3}\,\Omega\,\mathrm{cm}^2$ after annealing for one minute at moderate temperatures, i.e. 450 °C or 500 °C, were obtained. Furthermore, several approaches to fabricate smooth mirror facets were investigated. Laser scribing is found to contaminate the device backside because of oxides redeposition, which hinders proper soldering and packaging. In this insight, wafer thinning and machine-assisted diamond scribing and cleaving are better suitable. Alternative cleaving methods were proposed as well, which may help achieving smooth facets when the crystal perfection of the GaN wafers is low and the stress induced by the epitaxial layers is large.

Based on these developments of the chip technologies, blue and violet narrow-ridge laser diodes suitable for packaging in TO-case and continuous-wave (CW) operation up to above 50 mW were fabricated. A process for controlling the facet reflectivity through deposition of dielectric mirrors was investigated as well. Applying an antireflective coating on the front facet and providing optical feedback by an external diffraction grating, a Littman-Metcalf external cavity diode laser (ECDL) was realized. This laser could be tuned over the spectral range 435 nm–444 nm and provided a peak emission power of more than 27 mW CW at 439 nm. As an alternative approach to obtain a narrow spectral linewidth, the feasibility of monolithically integrated Bragg-gratings was studied. Different device designs were discussed, and the most suitable options for the realization of GaN-based DFB laser diodes identified. A technological process was then developed, which allows the fabrication of 10th order Bragg-gratings (Bragg period 801 nm) with standard i-line projection lithography. High duty cycles of more than 0.9 were achieved by etching deep V-shaped grooves.

A peculiar property of (In,Al,Ga)N laser diodes is that, when the ridge is narrow, the threshold current strongly depends on the ridge etch depth. This phenomenon was investigated, in this work, by fabricating, characterizing and comparing laser diodes with different etch depths. For ridge widths below 2 µm, the threshold current of shallow-ridge devices was more than two times larger than that of comparable deep-ridge devices. Moreover, in the lateral far-field patterns of shallow-ridge laser diodes side-lobes were observed. This feature supports the hypothesis of strong index-antiguiding effects, which were studied by simulations. The mode behavior was investigated first using a 2D mode solver and a simplified gain model. The results confirmed the plausibility of the hypothesis: if antiguiding is strong and the ridge is shallow, the carrier-induced index change in the quantum wells can compensate the lateral index step. This, in turn, reduces the lateral optical confinement, which increases the threshold current and generates side lobes in the far-field patterns. By measuring the change of the mode effective index by increasing current, an antiguiding factor larger than 10 was experimentally determined, which is compatible with the value assumed in the simulations. Finally, the results were confirmed by self-consistent electro-optical simulations based on a more accurate device model. According to the results, in shallow-ridge devices the lateral diffusion of the charge carriers is enhanced due to antiguiding, and may have a large influence on the threshold current, as well.

Contents

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.

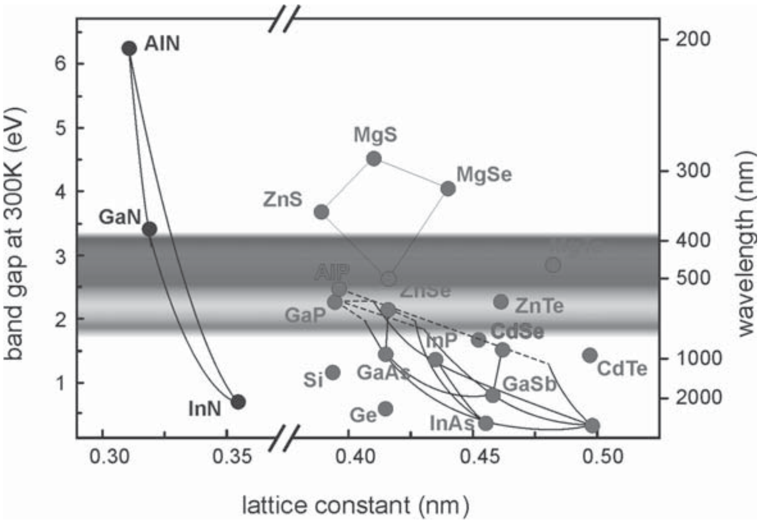


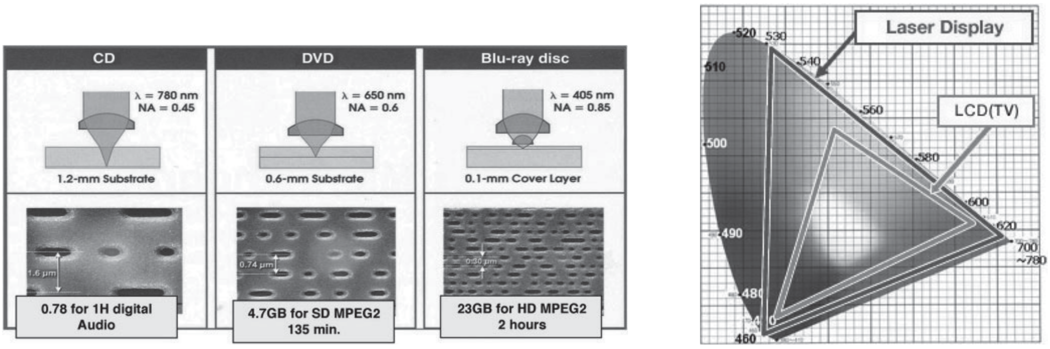
Figure 1.2: Bandgap vs lattice constant for the most common compound semiconductors (sources: [2] [3]).

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].

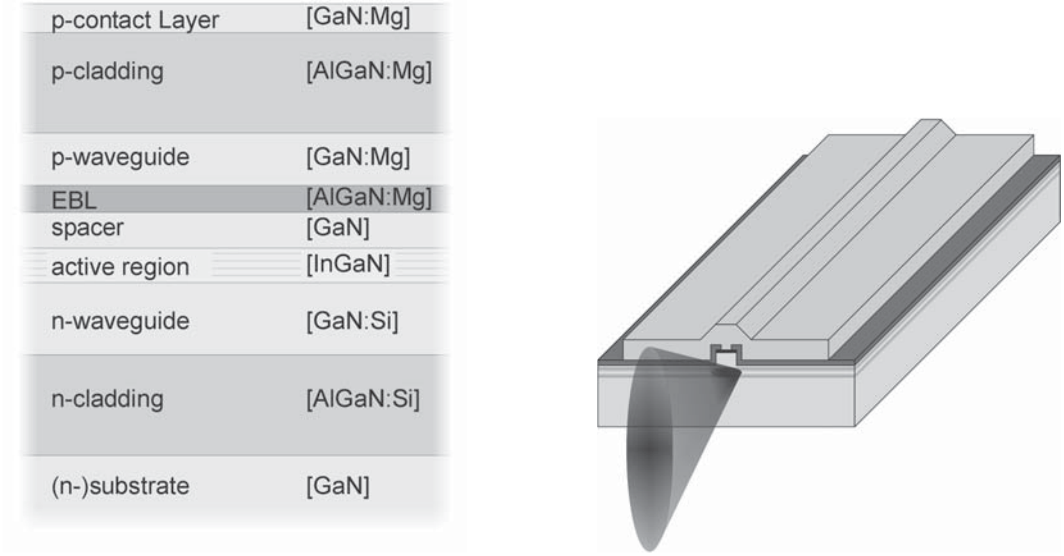
In laser diodes, the population inversion necessary for lasing is achieved by means of a *double heterostructure*. In the most simple case, it consists of three semiconductor layers, where a narrower-bandgap layer is sandwiched between two wider-bandgap *cladding layers*. Usually, the top layer is p-doped 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.