Chapter 1

Introduction to Photonic Quantum Dot Nanomaterials and Devices

Nanotechnology has revolutionised photonics, enabling us to conceive materials such as carbon nanotubes (CNT), quantum dots (QD) and metamaterials that have novel optical properties and enable functionalities right down at the materials level. This, however, has brought at least as many new challenges to our understanding in just how light interacts with matter on the nanoscale and also how matter is different when it comes in such small, nano- (but not atomic-) sized pieces. Indeed, for applications in optoelectronics, quantum dot nanomaterials show very promising characteristics allowing for the design of the spatial and spectral properties of propagating light fields. Using these materials for lasers (by applying a suitable electric contact and carrier injection) leads to a particularly high differential gain and low laser threshold current (Asada *et al.*, 1986), low alpha factor (Willatzen *et al.*, 1994) and ultrafast modulation properties (Kapon, 1999a). In this chapter we summarise the physical properties of photonic quantum dot nanomaterials and introduce the various types and configurations of photonic quantum dot devices. The theory that forms the basis for our study of the physics of photonic quantum dot nanomaterials and devices will be introduced in Chapter 2.

1.1 Physical Properties of Quantum Dots

The specific epitaxial structure of quantum dot nano systems implies a three-dimensional carrier confinement which leads to a spatial carrier localisation and discrete energy levels. As a consequence, ensembles of QD are very attractive for the development of novel gain media with properties specifically designed for a particular application. QD gain media that combine the advantages of semiconductors and atoms allowing for the design of highly coherent, tuneable and compact laser sources. Furthermore, compared to the GaAs-based material technology of bulk and quantum well structures, they allow generation of laser emission at longer wavelengths. Needless to say, this is of particular importance for telecommunication applications. The specific design of the active media also leads to many additional promising properties such as a reduced temperature sensitivity, atomic-like gain characteristics with reduced phase-amplitude coupling (α-factor) leading to good spatial and spectral purity, low chirp and reduced reflection sensitivity (reducing the need for optical isolators).

Semiconductor quantum dot nanomaterials are made by epitaxial growth technology, typically based on the principle of self-organised Stranski–Krastanov QD growth using molecular beam epitaxy (MBE) for exploratory materials development and the metal organic chemical vapour deposition (MOCVD) method meeting industrial standards. These methods allow the development of quantum dot materials at $1.3\,\mu$m and near $1.55\,\mu$m. In combination with a suitable design of wave guides, cladding, electronic contact and barrier layers, as well as of the laser cavity, allow the fabrication of photonic devices suitable for the industrial mass-market of information technology. In experiments, the physical properties (e.g. electronic structure, inhomogeneous broadening decay times) of quantum dot systems can be measured and detected with various methods: among the most important configurations are pump–probe setups (Berg *et al.*, 2001) and photoluminescence measurements (Chen *et al.*, 1998).

1.2 Active Semiconductor Gain Media

Generally, the fundamental principle of an active semiconductor medium is the recombination of electron-hole pairs in a suitable layer of semiconductor medium embedded in a chip forming an optical cavity for the optical fields propagating within it. Inversion of this medium is then realised by optical or electronic pumping via an optical pump beam, or directly via electrical contacts by applying a current. Once the pump beam or current reaches a characteristic threshold spontaneous emission processes are exceeded by stimulated emission and lasing starts.

The gain of an active semiconductor medium is the key element for the generation of coherent light realised in a laser configuration consisting of active gain medium, cavity and an external pump process. To achieve gain in semiconductor media, a characteristic density of electron-hole pairs has to be appropriately spatially localised. This may be realised by applying a current at the junction of a pn-diode. Today, most semiconductor (diode) lasers are based on III-V semiconductors. The active region of a typical system is based on GaAs and $\mathrm{Ga_{1-x}In_xAs}$ where the subscript x indicates the fraction of Ga atoms in GaAs that is replaced by In. Typical nano-structures based on $\mathrm{Ga_{1-x}In_xAs}$ emit — depending on expitaxial growth, structuring and doping — in the spectral window of 1.3 to 1.55 μm that is relevant for telecommunication. Without loss of generality, the numerical results presented in this book will refer to this material system and wavelength range. Depending on the geometry and thickness of the active layer one differentiates between bulk (heterostructure, three-dimensional '3D') or quantum well (two-dimensional '2D'), quantum wire (one-dimensional '1D'), and quantum dot (zero-dimensional '0D') nanostructures. Thereby, the dimensionality marks the number of dimensions the charge carriers effectively 'see'.

The physical properties of active nanomedia can be described on the basis of $\mathbf{k}\cdot\mathbf{p}$-theory. This approach allows the simulation of electronic and optical properties and naturally includes details on the size, shape and composition of the quantum dots. Typical geometries of quantum dots are pyramids or lens-shaped dots. Thereby, the vertical aspect ratio may, as well as the composition, vary from system to system. Since some of these parameters are known, or can only be measured very inaccurately, it is also possible to vary the most crucial structural properties like size, shape, composition or composition-profile systematically in the modelling. This eventually provides all essential electronic and optical properties that can be integrated in a space-time model.

1.3 Quantum Dot Lasers

Many novel laser structures use the promising properties of quantum dots. In these systems, a quantum dot layer is embedded in vertical and lateral directions in a multi-layer structure. The active medium represented by the quantum dot ensemble allows the generation of stimulated emission required for the lasing process. Combined with a form feedback by an optical resonator (realised by the natural reflectivities of the material or by a specific grating structure) one thus obtains a lasing structure with promising spatial and spectral emission properties. The excellent output characteristics of these nanomaterials thereby is a direct result of the strong carrier localisation and the discrete level structure characterising a quantum dot ensemble. In the following we will introduce two typical resonator structures employed in quantum dot laser devices. For details we refer the reader to the detailed discussion in (Coldren and Corzine, 1995; Diehl, 2000; Kapon, 1999a; 1999b).

1.3.1 *Heterostructure lasers*

Semiconductor (double) heterostructure lasers consist of at least three semiconductor layers sandwiched on top of each other (Thompson, 1980; Yariv, 1989). The middle layer, the active zone, has a smaller band-gap than the two outer ones, the cladding layers. These layers form a pn-junction. The thin active region is usually un-doped or slightly doped p-type, while one of the adjacent layers is heavily doped p-type and the other one n-type. Application of a positive bias current leads to an injection of electrons from the n-type layer into the active layer and to a creation of holes in the p-side. The potential barriers resulting from the energy difference between the energy gaps of the different compound semiconductors thereby prevent the diffusion of the charge carriers out of the active region into the p- or n-type layer. Furthermore, the energy of the optical mode is confined to the central active layer: the different doping of the layers leads to a spatial index profile and thus to the formation of a dielectric waveguide in the vertical direction for the optical fields propagating in the structure. Many of today's mass-produced semiconductor lasers still rely on the principle of the double confinement (of carriers and radiation) realised in the double heterostructure.

1.3.2 *Active nanomaterials*

Generally, a large number of semiconductor materials can be used to manufacture quantum structures. In addition, one can combine different semiconductors with favourable properties in an alloy. This variation of input parameters is usually referred to as band-gap engineering. Band-gap engineering opens fascinating possibilities, in particular for fabrication of novel laser structures (Yariv, 1989) and the tayloring of emission wavelengths. The best controlled III-V quantum system is the GaAs/AlGaAs structure with emission in the red range (Yariv, 1989). Another attractive material showing significant advantages over the conventional long wavelength structures is the quaternary alloy GaInAsN, which was first proposed by (Kondow *et al.*, 1996). Good temperature characteristics and simpler fabrication makes GaInAsN VCSELs very attractive for applications in high-speed optical networks (Nakatsuka *et al.*, 1998; Nakahara *et al.*, 1998; Sato *et al.*, 1997).

Today advanced semiconductor growth techniques allow realisation of a semiconductor structure with a precision down to a single atomic layer. This has pushed forward the development of mesoscopically structured semiconductor systems. If an active semiconductor layer is sandwiched between semiconductor material of larger band-gap a quantum well is formed between the barriers and a confinement of the carrier dynamics in one spatial direction occurs. Typical layer thicknesses are a few nm, i.e. a limited number of atomic layers. The restriction on the movement of the carriers in a two-dimensional plane leads to quantisation effects and thus also affects the carrier energy as compared to a 'free' electron in a bulk medium: the system now is characterised by allowed energy bands whose energy positions are dependent on the height and width of the barrier. Details of the energetic structure can be calculated by means of fundamental quantum mechanics.

Due to their discrete, atom-like energy level structure, semiconductor quantum dots have unique electronic and optical properties and thus are ideal for novel laser devices based on mesoscopically structured materials. The good spatial and spectral purity of these systems is a direct consequence of the confinement of the electronic wave-functions in all three spatial dimensions leading to discrete energy levels and to a strong localisation of carriers. In recent years, rapid progress in the epitaxial fabrication of self-assembled III/V QDs has triggered tremendous efforts to use them as a gain medium in semiconductor lasers (Bimberg *et al.*, 1998). QD lasers show many advantageous properties, such as low and almost temperature-independent threshold current densities, high material gain (Arakawa and Sakaki, 1982) and low amplitude-phase coupling (α-factor) (Diehl, 2000). Today, QD lasers exhibit threshold current densities similar to good quantum well (QW) lasers but show a much higher beam quality (Asada *et al.*, 1986). Furthermore, the potential of QDs for being used in lasers with high-power outputs and extended wavelength ranges has attracted additional interest. In particular, the possibility of fabricating QD lasers emitting in the 1.3 μm wavelength region that are grown on inexpensive GaAs substrates and can be intetrated with existing III/V technology appears extremely interesting for telecommunication applications (e.g. signal processing, switching, wavelength division multiplexing) in the spectral window of minimum dispersion in glass fibres.

1.4 Laser Cavities

Concerning the geometry of the laser resonator, one generally differentiates between the families of edge-emitters (or in-plane lasers) and vertical-cavity lasers (or surface-emitters).

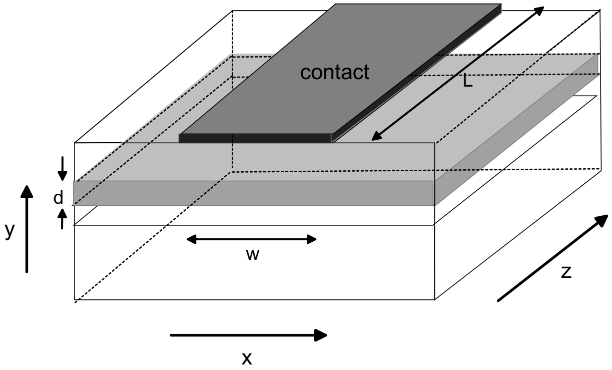

Fig. 1.1. Schematic of the geometry of an edge-emitting semiconductor laser. Charge carriers injected through the contact region at the top of the device (*dark grey*) recombine in the active zone. The active layers of the edge-emitter are located between the cladding layers. Light, generated by stimulated emission and amplification, propagates in the longitudinal (z) direction.

1.4.1 *In-plane edge-emitting lasers*

In an *edge-emitting* laser or amplifier (Fig. 1.1) carriers are injected via the contacts on the top. The carriers are captured by the dots embedded in the xy area. In the vertical direction, the dots are aligned in stacks (in approximately three to ten layers). Light generated by electron-hole recombination then travels in the longitudinal (z) direction inside the cavity formed by the two mirrors at the front and back. The length L of the cavity typically ranges from a few hundred μm to 3000 μm). This guarantees a sufficient gain during the propagation of the light fields in the resonator. The comparatively small thickness (about 0.1 μm) of the active layer in the vertical (y) direction resulting from the semiconductor epitaxial layer structure assures a vertical guiding of the optical waves. The transverse (x) may be considerably larger (about 3–5 μm for a single-mode laser and 50–200 μm in case of a multi-mode high-power broad-area laser). These typical dimensions of the active area strongly suppress one of the polarisation directions and thus lead to the emission of linear polarised light.

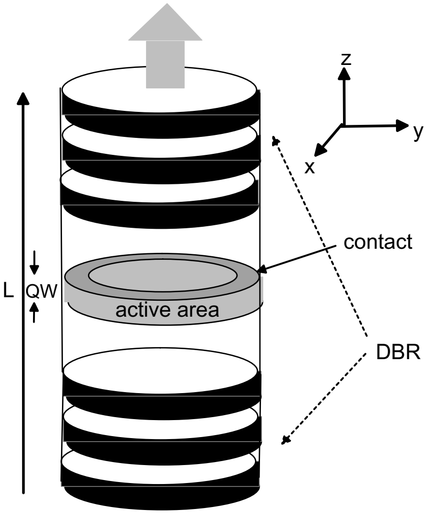

Fig. 1.2. Schematic of the geometry of a vertical-cavity surface-emitting laser (VCSEL). The active layers of the VCSEL are located between distributed Bragg reflector (DBR) layers.

1.4.2 *Vertical-cavity surface-emitting lasers*

In *vertical-cavity surface-emitting* lasers (Fig. 1.2) (VCSELs), the geometry of the cavity is completely different. Most notably, the length of the resonator now only measures about one wavelength. Consequently, only a single longitudinal mode will be dynamically relevant and propagation effects may be disregarded. At the same time, both transverse (x and y) directions are equally large (typically 3–30 μm). One has to therefore consider two transverse dimensions in theoretical approaches. Dielectric multilayers at both ends of the cavity lead to high mirror reflectivities and guarantee high gain. In the active area of the VCSEL, the recombination of an electron-hole pair leads, with equal probability, to the two possible polarisation directions. It is therefore, in particular, the resonator geometry or the epitaxial structure that determines the polarisation properties of the emitted radiation. Furthermore, due to the symmetric geometry, the polarisation of the emitted light is highly sensitive to the microscopic carrier and light field dynamics, anisotropies in the crystal structure or strain and optical anisotropies in the mirrors. As a consequence, VCSELs may exhibit polarisation instabilities in the input–output characteristics, which are the limiting factor in polarisation-sensitive applications. In theoretical approaches this can be considered by explicitly calculating the dynamics of microscopic dipoles and the light field dynamics for the two possible polarisations.

1.4.3 *High-power laser amplifiers*

Modern applications in nonlinear optics or telecommunications require laser sources offering good spatial and spectral purity, high output power and ultrafast response to high-speed modulation. The amplification of a coherent light single (e.g. a single-stripe laser) in the active area of an antireflection-coated large-area semiconductor laser (Bendelli *et al.*, 1991; Goldberg and Weller, 1991; Goldberg, *et al.*, 1992, 1993; Mehuys *et al.*, 1993, 1994; Mukai *et al.*, 1985; O'Brien *et al.*, 1997; Parke *et al.*, 1993; Sagawa *et al.*, 1996; Saitoh and Mukai, 1991) allows the generation of coherent light with such properties. During propagation, injected light basically maintains its spatial and spectral properties (Goldberg *et al.*, 1993). Up to now, various amplifier systems have been realised (broad-area amplifiers in single-pass or double-pass configuration, amplifiers with tapered geometry). In particular, the tapered amplifier (Fig. 1.3) has, due to its small signal gain and good wave-guiding properties, been the focus of theoretical (Hess and Kuhn, 1996; Lang *et al.*, 1993; Moloney *et al.*, 1997) and experimental (O'Brien *et al.*, 1997; Walpole, 1996) investigations. It consists of two parts, a single-stripe waveguide with a width of $\approx$3–5 μm and a tapered section in which the active area enlarges in the propagation direction so that the intensity at the output facet is kept below the threshold value for catastrophic optical mirror damage (COMD). The facets of the tapered amplifiers are anti-reflection coated. For good beam quality, this facet reflectivity should be less than 10^{-4} (Berg *et al.*, 2001). Alternatively, the wave propagation in the resonator should be off-axis, i.e. the facets should be angled with respect to the resonator axis. The small transverse dimension of the waveguide at the input facet of the active area leads

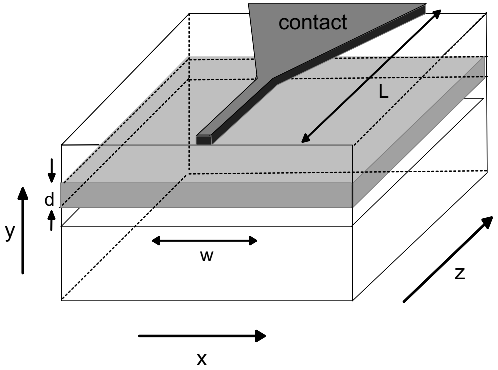

Fig. 1.3. Scheme of a large-area semiconductor laser with tapered geometry.

to a high small-signal gain allowing efficient saturation of the inversion within the active layer for very moderate input powers of a few mW. Typical lengths of the small waveguide are a few 100 μm at a total length of 1–3 mm of the device.

1.4.4 *Coupled-cavity systems*

Coupled-cavity systems (Fig. 1.4) consist of two separately contacted sections in direction of light propagation, represent another promising configuration allowing for a separate optimisation of a pulse generation process (in the current-modulated short section) and the pulse amplification process (in the long second section).

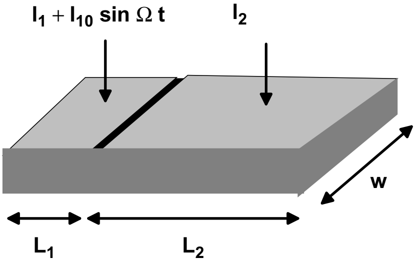

Fig. 1.4. Scheme of a two-section laser.

1.4.5 *Optically excited nano systems*

The emission properties of semiconductor laser structures with large extension of the active area typically is strongly determined by the spatio-temporal coupling and interplay of light propagation, diffraction, carrier diffusion and microscopic carrier scattering processes leading to dynamic optical patterns (filamentation). Recently, the realisation of optically pumped semiconductor lasers (typically a vertical-cavity surface-emitting laser in external resonator configuration) has attracted attention. This concept allows for a combination of the power scaling involved in the high gain of semiconductor laser devices and the high beam quality provided by direct optical excitation. Optically pumped nano VCSELs thus combine the advantages of VCSELs and large-area laser amplifiers. They thus represent promising light sources for future laser technologies and applications. Furthermore, a spatially selective optical excitation and the resulting localisation or transfer of light may open the way to future quantum memories.

1.4.6 *QD metastructures*

In recent years, improvements in material technology have enabled the design of novel nano-structures with a specific spatial structuring combining the tailoring of the properties of propagating light fields with the design of the localised dot emitters. Embedding semiconductor quantum dots in micro-cavities allows an additional engineering of the photonic emission characteristics. In such a system the micro-cavity is of the order of the wavelength of the emitted light. As a consequence, compared to edge-emitting lasers the emission pattern and even the local spontaneous emission rate can be controlled more efficiently. Recent work on semiconductor quantum dot micro-cavities focused on the enhancement of spontaneous emission in microposts (Pelton *et al.*, 2002) or on an analysis of whispering-gallery modes in microdisks (Gayral *et al.*, 1999). Future systems on the basis of a semiconductor quantum dot in a micro-cavity small enough to contain only one mode resulting in a dot-in-a-dot system, may enable the generation of controlled single photon emission. This represents an important basis towards novel quantum communication and cryptography schemes (Waks *et al.*, 2002). Furthermore, micro-cavity lasers are also of great interest for future low power applications and, due to their fast response, to external pumping, potentially in high-speed optical communications.

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