1. Introduction

1.1. History

The 20th century saw the appearance of many new man-made materials, of which many never existed on earth before either in quantity or quality. Apart from purified radioactive elements used in atomic weapons or nuclear fission reactors and the petroleum derived polymer chemistry, semiconductor material sciences are among the most defining technologies shaping the later half of the last century [ELI14]. They not only gave rise to solar cells, diodes, LEDs and super-sensitive photodetectors, but grew to become the backbone of modern information technology since the first fabrication of a transistor by Shockley, Bardeen and Brattain in 1948. Silicon based microchips and controllers are used in smartphones, TVs, cars, planes, and even satellites and are therefore virtually omnipresent in our every day lives. The theoretical description of semiconductors had to match the rapid advancement made possible by ever more sophisticated fabrication techniques and the history of solid states physics is intrinsically linked with the development of quantum mechanics.

The concept for a semiconductor laser was first published by Basov *et al.* [BAS61] in 1961, only one year after the first experimental realisation of a laser by T. H. Maiman at Bell Laboratories in 1960 [MAI60]. But as opposed to this optically driven ruby laser, Basov *et al.* described a scheme for an electrically driven laser by recombination of charge carriers injected across a p-n junction. After some initial success, when in 1962 three independent groups produced the first semiconductor lasers, progress was slow [CHO99]. This was due to the fact that existing semiconductor technology was based solely on silicon. Silicon, however, does not exhibit a direct bandgap and is therefore not suited for use in laser systems. On the other hand, compound semiconductors were less well understood and fabrication was hard, so that the first lasers were only operable at cryogenic temperatures and only for a short pulse [BIM12]. For a more detailed history of the diode laser see Ref. [ELI14] and references therein.

The principle of an electrically driven semiconductor laser is shown in Fig. 1.1 (from [CHO99]). Here, the lower edge of the conduction band and the upper edge of the valence band is sketched together with the equilibrium electron density (shaded areas). With no voltage applied (a) the Fermi-energy is constant throughout the device and there are no regions where electrons could relax into unoccupied valence-band states. However, when a bias is applied in forward direction (b), electron-hole recombination becomes possible in the plane of the p-n junction.

This basic design is still used today in all electrically driven semiconductor lasers, commercial or otherwise. Among which there now exists a wide variety of different kinds, e.g. quantum well (QW) or quantum dot (QD) lasers. The great advantages of semiconductor lasers are not only low threshold currents and continuous wave (cw) output, but especially their small size, high temperature stability, room temperature operation and relatively cheap fabrication, all of which paved their way towards the wide use they are seeing today [BIM12].

This work will focus on a specific subset of semiconductor lasers, namely quantum dot lasers with two simultaneous lasing emissions. The stability of these lasing

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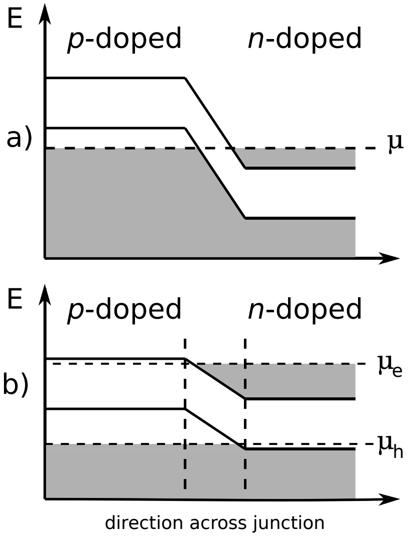

Figure 1.1: Energy band sketch of a *p*-*n* junction perpendicular to the junction plane (figure redrawn from *Semiconductor-Laser Fundamentals* by W. Chow and S. Koch, Springer (1999) [CHO99]). Without a voltage applied (a) the electrons (shaded areas) relax below the global Fermi-energy μ. For applied voltage in forward bias (b) electrons and holes can recombine at the *p*-*n* junction, enabling lasing.

states, originating from the ground state and excited state of the quantum dot, will be investigated temporally and parametrically. Especially the current induced appearance of excited state emission and subsequent quenching of ground state emission will be studied numerically and analytically. The suitability of these types of quantum dots for optical data transmission will also be touched upon, before the results of an experiment performed by the group of Prof. Woggon will be presented, numerically reproduced and interpreted.

1.2. Quantum Well and Quantum Dot Lasers

In 1963 Herbert Kroemer proposed [KRO63] to use a sandwich-like structure for the *p*-*n* junction. The charge carriers should be injected through an outer material layer with a high bandgap, while the active zone for the lasing should be fabricated from a smaller bandgap compound. The carrier density in this narrow region could then exceed the carrier densities of the injectors, which is impossible for a homogeneous structure. This enhances conversion of electrons into light and should be usable to reach higher quantum efficiencies and therefore lower threshold currents. There was, however, no sample fabricated at that time.

Independent of this, Charles Henry, who was working at Bell Laboratories, noticed that wave-guiding technology, which was used at that time to control the dominant direction of emitted laser light, could also be used to guide electron waves. The thickness, however, needed to be reduced below the de-Broglie wavelength of the electrons, so that the confinement became effective. A prototype was fashioned together with R. Dingle, exhibiting greatly reduced threshold currents. In 1976 a patent was filed, detailing the principle of quantum confinement for enhancing laser operations [DIN76].

When calculating the density of states of this structure, Henry obtained the remarkable result that it was not the known square-root dependence of three-dimensional structures, but a stepwise function due to discrete energy levels caused by the confinement in one direction (see Fig. 1.2). He concluded that this finite density of states, even for the lowest attainable energy, greatly enhanced laser operation. As only carriers of these lowest energies are participating in the electron-hole recombination, their increase in numbers leads to a higher optical gain and hence laser output for lower injection currents.

Obviously, charge carriers can be confined in more than one dimension, if different semiconductor heterostructures are grown. If the dimension is smaller than the de-Broglie wavelength in two directions, the resulting object is called a nanowire. When charge carriers are confined in all three dimensions, the structure was originally called quantum box and is nowadays called a quantum dot (QD). The resulting density of states is shown in Fig. 1.2. Each additional confinement increases the density of states at the lowest energy, and is followingly expected to increase laser performance.

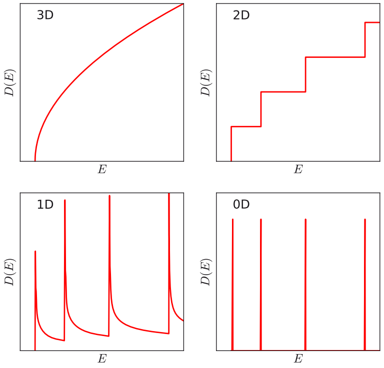

Figure 1.2: Density of states versus energy for electronic states with different dimensions. Lasing recombination usually involves the carriers of lowest energy, so the finite density of states even for the lowest occupiable state in the 2D case is favourable for laser operation. Going to even lower dimensions further strengthens this effect.

Quantum dots (QDs) even display a discrete spectrum of energy states. As this resulting spectrum, both for holes and electrons, is very similar to the discrete eigenstates of atoms, they are labelled in the same fashion: The lowest energy state is called ground state (GS), the next higher state the 'first excited state' (ES) and so forth. Generally, the number of confined states depends on the size of the quantum dot. Due to fabrication processes the confinement in reality is less than perfect. Therefore, the eigenstates of the quantum dots are usually modelled within a parabolic potential, however more advanced modelling approaches also exist [SCH07f]. Figure 1.3 shows a sketch of the energy bands and localised states for a quantum dot.

Confinement also gives rise to a zero-point energy, so that the energy separation

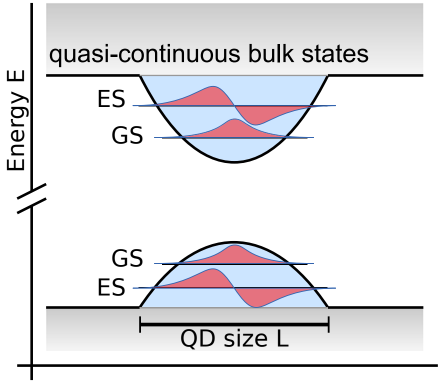

Figure 1.3: Energy sketch of valence and conduction band of a quantum dot for a parabolic potential. The QD is fabricated from a lower-bandgap material than the surrounding bulk material, the confinement in all three dimensions giving rise to discrete energy levels. Due to their similarity to atomic states, they are labelled ground state (GS), first excited state (ES) and so forth.

between electrons and holes for the GS of the nanostructure is not simply given by the band gap of the material. Hence, the resulting optical transition of frequency ω possesses the energy $\hbar\omega = E_{bandgap} + E_0$. As in the quantum mechanical example of a particle in a box, this zero-point energy E_0 is size-dependent. This effect is present in quantum wells, wires and dots and is often exploited for changing the wavelengths of emitted light by changing the confinement size L. Naturally, there are limits for tuning the wavelength like this, as structures can neither grow too big nor too small, and followingly there is still a wide variety of material systems used today for obtaining lasers from infrared to ultraviolet.

Now, several theoretical groups predicted during the 1980s, that quantum dots would exceed even quantum wells in their performance [ARA82, ASA86], so that the attention was shifted towards fabricating these new types of nanostructures. QDs have yet to fulfil these promises, as it turned out that carrier injection into the quantum dot is a limiting factor for lasing operation and thus they remain a topic of major industrial and scientific interest even today.

This work will focus on typical self-assembled InGaAs quantum dots, though many of the findings presented here should also be valid for other material systems. Self-assembled InGaAs quantum dots are produced by Stranski-Krastanov growth either in molecular-beam epitaxy (MBE) or metal-organic vapour-phase epitaxy (MOVPE). In the critical step of this procedure, indium arsenide is grown on gallium arsenide in a thin layer, ranging from one to three monolayers. As Gallium arsenide and indium arsenide have a lattice mismatch of 7%, this leads to a highly stressed surface. During this stage and possibly during a short heating phase applied thereafter, the indium arsenide surface breaks open and reassembles itself into pyramidic structures. These pyramids are energetically more favourable, due to their tops being less stressed, for a certain temperature range during the growth process.

Afterwards, these QDs are overgrown with another layer of gallium arsenide, to form a dot-in-a-well structure [KOV03], which shifts the output wavelength to

1.3μm. As the creation process is stochastic, the sizes and shapes of the QDs are statistically distributed. Together with the inability to predict the exact spot where a QD will appear, this is arguably one of the the main disadvantages of contemporary QD technology. Their emission spectrum is broadened by their different sizes and compositions, and only a part of the QD ensemble is able to participate in the lasing process [BIM99, LUE11a, RAF11].