Vertical (external) cavity surface emitting laser: V(E)CSEL

Semiconductor disk lasers allow for a lot of new application possibilities and have many advantages as compared to conventional edge emitting semiconductor lasers. With the invention of the first surface emitting lasers (VCSEL) in 1979 by Soda et al. a completely new laser concept has been designed. Herein the resonator is perpendicular orientated to the crystal growth surface, which leads to a perfect circular laser beam profile. This is a significant benefit over edge emitting laser, whereof the elliptic profile aggravates many uses, e.g. laser beam adjustment/projection and light coupling into fibre.

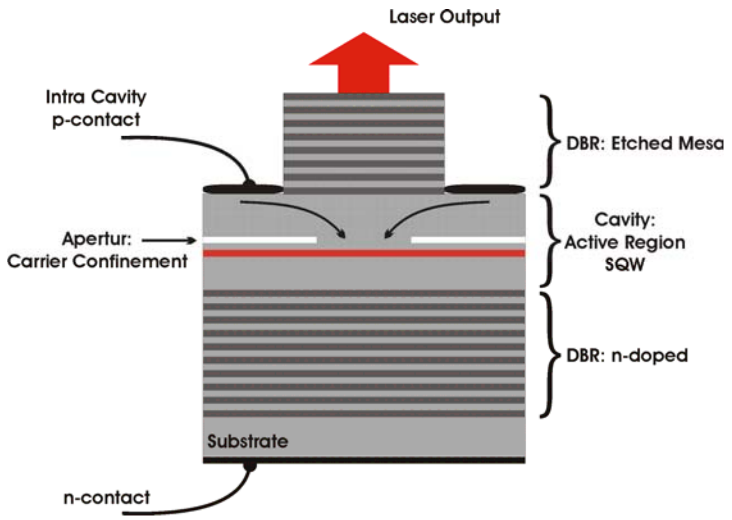

Figure 1: Exemplary sketch of a VCSEL. The electron injection occurs across the lower doped DBR whereas the holes injection is realised by an intra cavity contact. An aluminium oxide aperture ensures the essential carrier confinement.

Each cavity mirror of a surface emitting laser is a periodic layer stack of alternating materials sequences with high refractive index contrast, so called distributed bragg reflector (DBR), every layer having an optical thickness of a quarter of the laser wavelength. Multiple interference effects at each layer lead to high reflectivity of more the 99.9%, which is essential in a VCSEL to balance the short axial length of the gain region. This gain region in between the two DBRs is generally a strained multi quantum well hetero structure (MQWH) of about 10nm thickness, see figure 1 and 2.

In common VCSELs the upper and lower mirrors are p- and n-type doped, forming a diode junction. In more complex structures, the p- and/or n-doped regions are buried between the undoped mirrors. This concept requires also a more complex fabrication process to contact the device, see figure 1, but avoids electrical power loss across the DBR. The relative short micro cavity in line with an etched mesa structure facilitates single mode operation of the laser diode. Another advantage of VCSEL is the low threshold current. Because of the relative small gain region electrically pumped VCSEL devices have low output power. Nevertheless, it is still sufficient enough for a lot of novel applications, e.g. telecom data transmission.

Optical pumped semiconductor disk lasers (VECSEL) with an external cavity allow for high output power scaled by the pump beam. In this layer design the upper DBR is replaced by an external mirror. Because of the optical pumping the active region can be extended to larger number of QWs, which leads to higher gain, see figure 3 and 4. Output powers of tens of watts can be achieved, if the disk laser is mounted to an effective heat sink. Particularly the external cavity enables the adjustment of non linear optics for second harmonic generation, e.g. infrared light is converted into visible laser light. Therefore laser devices with high output power and circular beam profile can be realised also in the visible spectral regime for various novel applications, e.g. “laser TV” and mini-projectors [1].

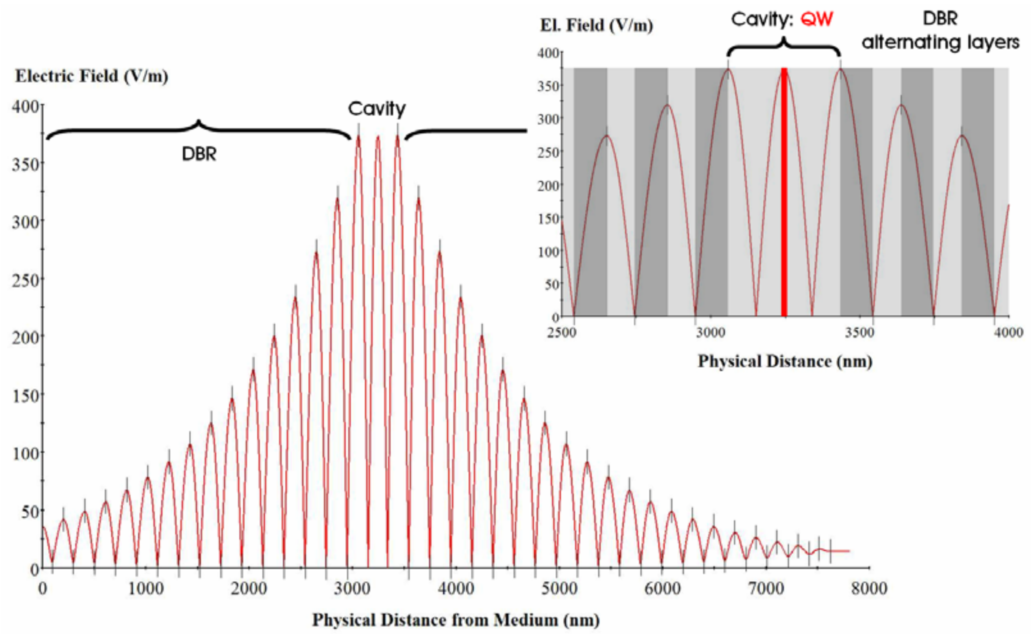

Figure 2: Spreading of the electric light field in a VCSEL. Interference effect at the interface of each alternating layer leads to a decrease in field intensity into the DBR structure. The QW (active region) is placed at an electric field maximum for optimal gain, see inset.

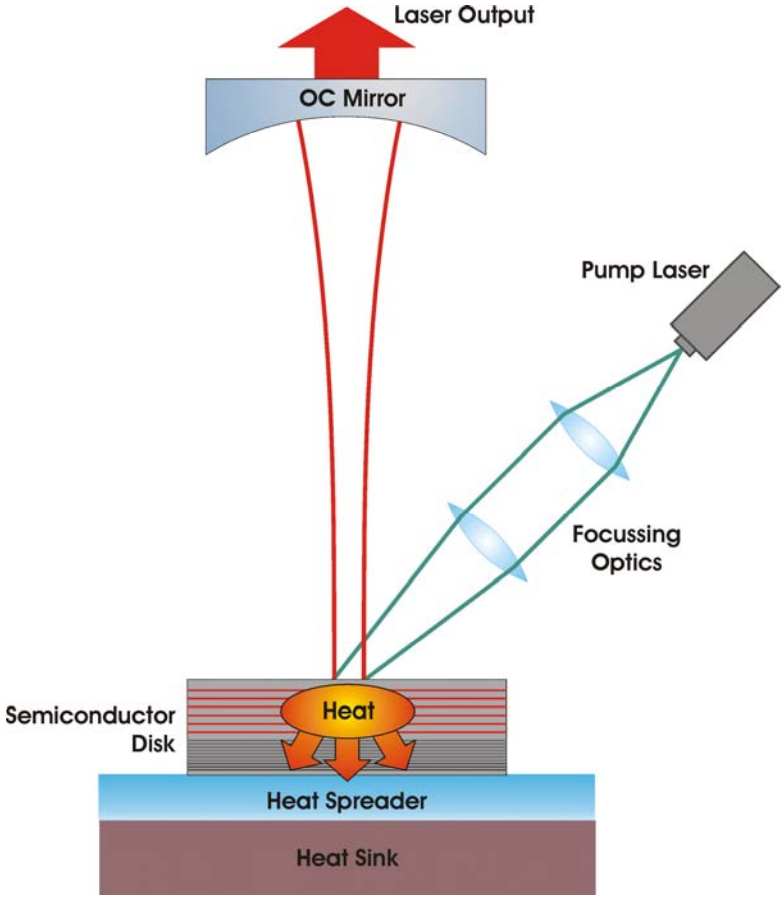

Figure 3: Principle setup of a VECSEL. The semiconductor disk laser is mounted to a heat sink in order to guarantee an effective heat removal. A non linear optic adjusted into the external cavity allows for second harmonic generation.

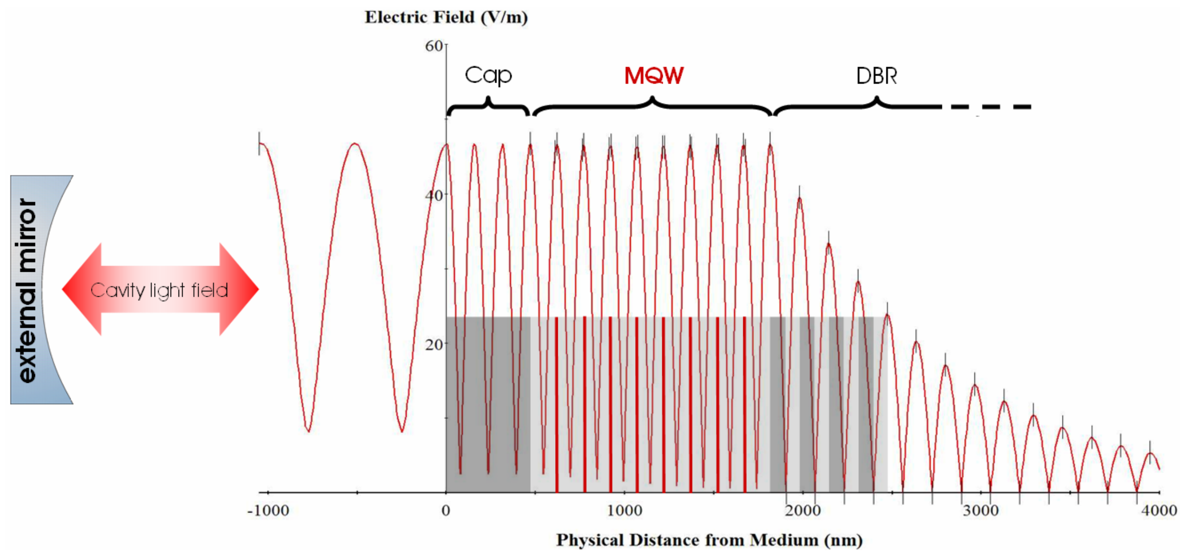

Figure 4: Spreading of the electric light field in a VECSEL. For an accurate thickness of the cap layer and the MQW structure the incident light field couples into the semiconductor disk without any intensity losses. Each QW is adjusted to a maximum of the electric field indicated by the red line in order to attain high gain.

The dedicated realization of VECSEL device structures requires a thorough knowledge of the physical properties as well as the epitaxial growth conditions of these complex semiconductor devices. Thus, the research group at the Philipps-University Marburg (Germany) have adopted an interactive approach from full microscopic design and theoretical modelling (Prof. Dr. S.W. Koch) to epitaxial realization by metal organic vapour phase epitaxy (MOVPE) and detailed experimental characterization. Applying this approach VECSEL layer structures from emission wavelengths at 980nm, 1040nm, 1178nm and 1260nm have successfully been realized.

So fare the main focus has been on laser in the infrared emission regime based on GaAs substrate. The ternary material system (GaIn)As acts as an active region for emission up to about 1200nm, whereas longer wavelength can be achieved with the quaternary diluted nitride (GaIn)(NAs).

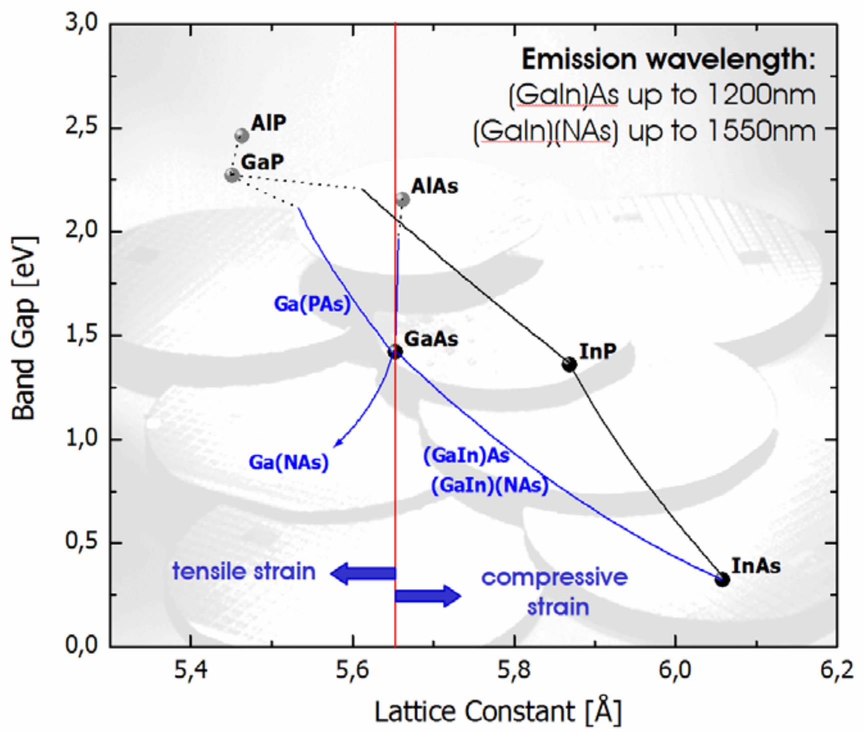

Figure 5: Energy gap versus the lattice constant of III-V semiconductors. The incorporation of In and N into GaAs lowers the energy gap of the compound semiconductor. At the same time In leads to an increase and N to a decease of the lattice constant. P in Ga(PAs) rises the band gap and decreases the lattice constant.

The incorporation of In into GaAs leads to an increase of the lattice constant. Therefore the pseudomorphical growth of (GaIn)As and (GaIn)(NAs) with high In content, respectively, is only possible as high compressively strained thin QWs. With the aim of growing a thick MQW structure with a high number of QWs, precise strain compensation is of crucial importance. The ternary compounds Ga(NAs) as well as Ga(PAs) have a smaller lattice constant than GaAs and consequently are suitable as a barrier materials for the strain compensation of the whole MQW stack. Ga(PAs) with a larger band gap than GaAs will ensure a better carrier confinement in the QWs whereas Ga(NAs) with a lower band gap allows for a pump wavelength, which excite carrier in the barrier with low excess energy, see figure 6. The final device application will determine the optimal choice of barrier material and the layer design.

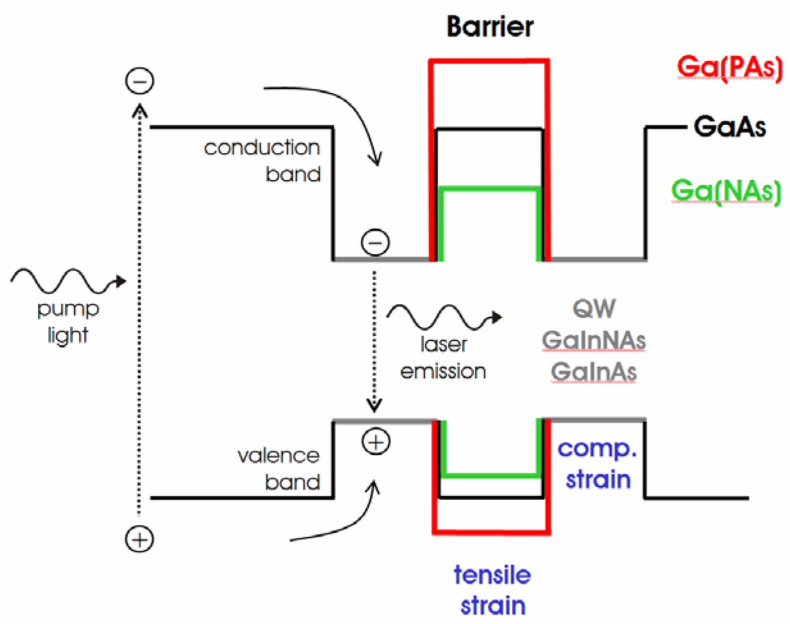

Figure 6: Band structure constellation for different tensilely strained barrier materials. Ga(PAs) leads to a higher hetero offset and a better carrier confinement in the QW as GaAs. The decreasing band gap of Ga(NAs) allows for a carrier excitation in the barrier with lower excess energy.

The complete realisation of VECSEL devices requires thorough knowledge in III/V epitaxy of various material systems in addition to various experiences in structural characterisation techniques in order to achieve the exact optical layer thickness and strain compensation.

The research activities at the Philipps-University Marburg include a wide range of materials systems based on GaAs, InP and GaP substrate. One of the main foci are dilute nitrides. From the application point view this novel class of III/V semiconductor has gained a lot of interest due to its strong band gap bowing and hence long emission wavelength. One the other side the controlled growth of highly strained layers demands a basic understanding in structural properties of dilute nitrides [2, 3].

Under headship of Dr. Stolz and in close cooperation with different institutions (Infineon Technology, Osram Optoelectronic, University of Tucson) various types of vertical cavity surface emitting laser have been realised [4, 5, 6] at the Material Science Center.

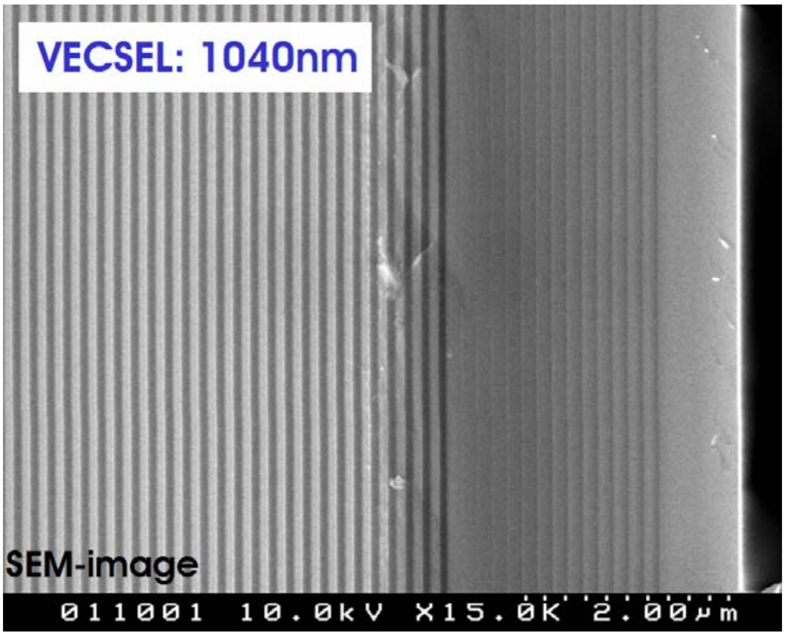

Figure 7: Scanning electron microscope image of a VECSEL. The dark and light alternating layers on the left side belong to the DRB. Each single QW of the RPG structure is indicated by a thin line in the left part of the device.

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