New concept for the monolithic integration of optoelectronic circuits on Silicon substrate: Silicon Photonics

Motivation

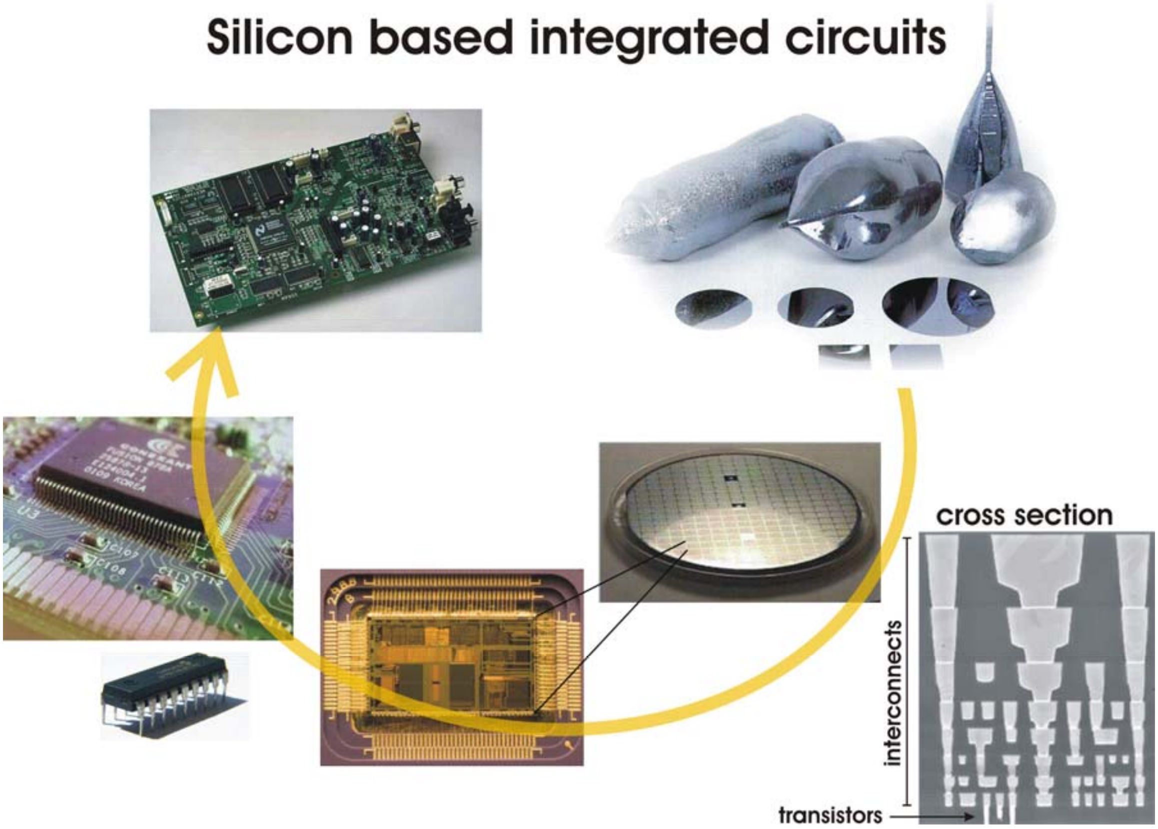

Figure 1: In a complex CMOS process, semiconductor devices like transistors and electrical interconnects are integrated on a Silicon wafer. After dicing, contacting and packaging the chip is mounted onto a computer board.

The most important semiconductor in our high-technologic developed society is Silicon (Si). Nowadays, complex information technology is completely founded on electronic data processing in Silicon based integrated circuits (ICs). It developed rapidly in the last fifty years starting with the invention of the first integrated circuit in 1959. At present time, there is one single dominating Si-technology: CMOS (complementary metal-oxide semiconductor), and thus, there are many big companies and a pronounced industrial infrastructure worldwide to manufacture Silicon chips according to the CMOS process, see figure 1.
This unique position of Silicon is based on several major advantages over other semiconductors:

- It is widely available and simple to purify.
- It is easy to handle and to manufacture.
- It has good thermal and mechanical properties.
- In combination with Silicon oxide there are further advantages for chip processing techniques (diffusion barrier, surface passivation, insulator, etc.).

The rapid progress in the miniaturisation of the Si-based integrated circuits has always granted improved properties at lower cost for the next computer generation in the last decades. This integrated chip development can be described by Moore`s law [1], which was already proposed in the 60’s. It says that the number of transistors on an integrated circuit is doubled every two years. The fulfilment of this early prediction can be seen in astonishing agreement in the processor development at Intel, see figure 2.

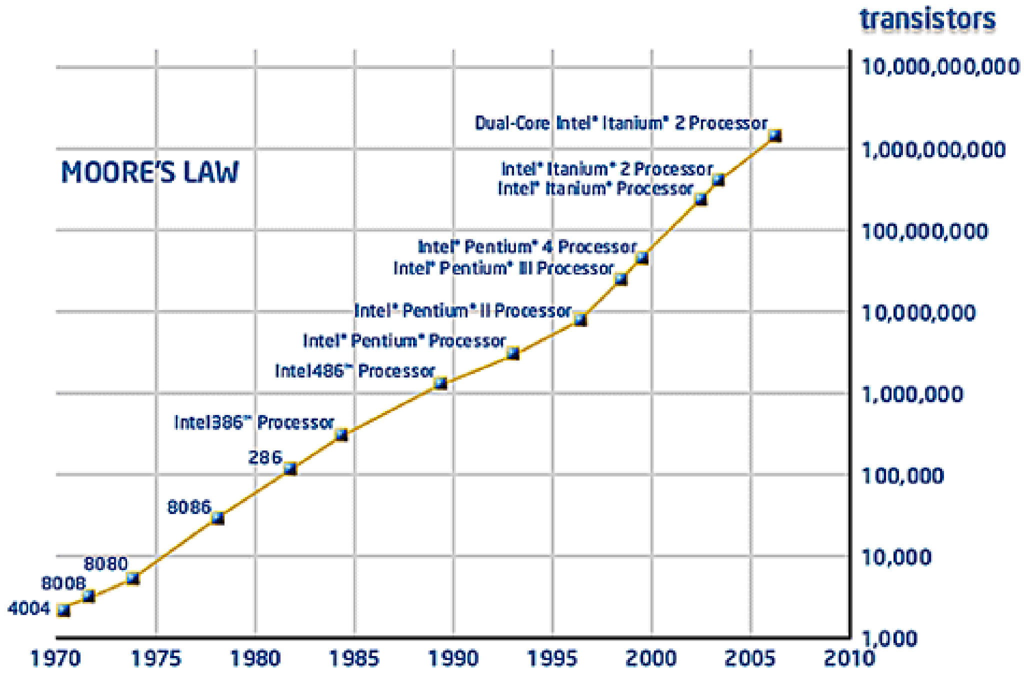

Figure 2: Number of transistors integrated into processors and other leading platform ingredients at Intel in the last forty years [2]. According to Moore’s law the number of transistors on an integrated circuit is doubled every two years

While the size of integrated interconnects and semiconductor devices decreased to enhance the computing power, the use of “pure” electrical interconnects leads to certain drawbacks as the gate width is continuously shrinking:

- RC delays due to the reduction in dimension and increase in density of the metal lines, see figure 3.
- Electrical signal latency and cross-talk.
- Increasing total interconnection length per unit area on the chip, which requires a high complex IC architecture.

To circumvent these obstacles, there is a strong world wide activity to investigate new material systems for the current CMOS fabrication technique and novel chip designs.

Nevertheless it is a question of time, when Moore’s law for “pure” electronic operating IC chips won’t be valid any more.

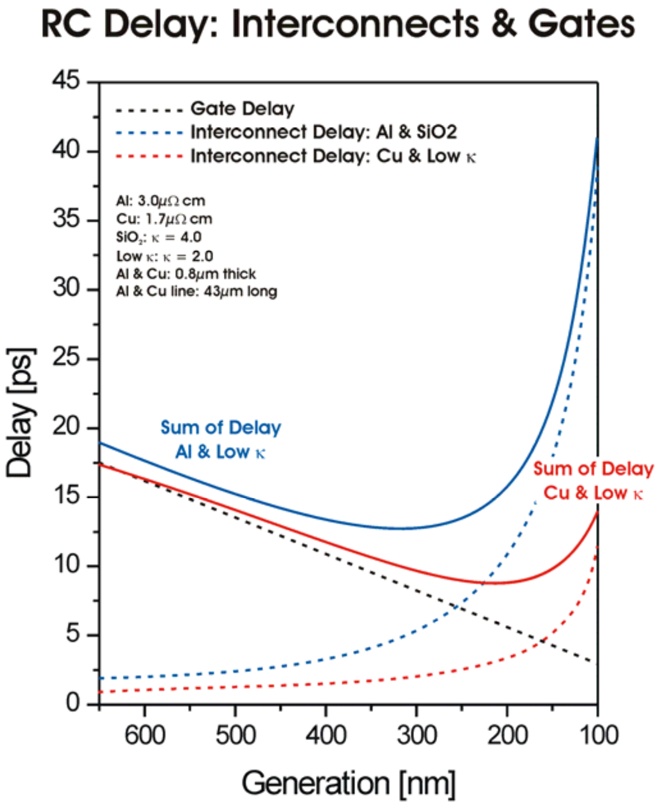

Figure 3: Contribution to RC delay from interconnects and gates as a function of the size [3]. Although the gate delay time decreases with reducing structure size, the high resistance of narrow interconnects leads again to an increase of the sum delay time.

At the same time, the application of data transfer by optical signals via fibre looms large in the information technology. Since the transfer rate operates close to the speed of light and the band width as well as the transfer range is much broader than for the electrical data transfer, the first application of fibre was settled for long distanced telecommunication already in the eighties. Nowadays optical data transfer also replaces electrical signals in local area networks or storage networks. This development obviously demonstrates that "optics" is moving towards the integrated chips and provokes a challenged forecast for the next achievements in optical data processing, see figure 4.

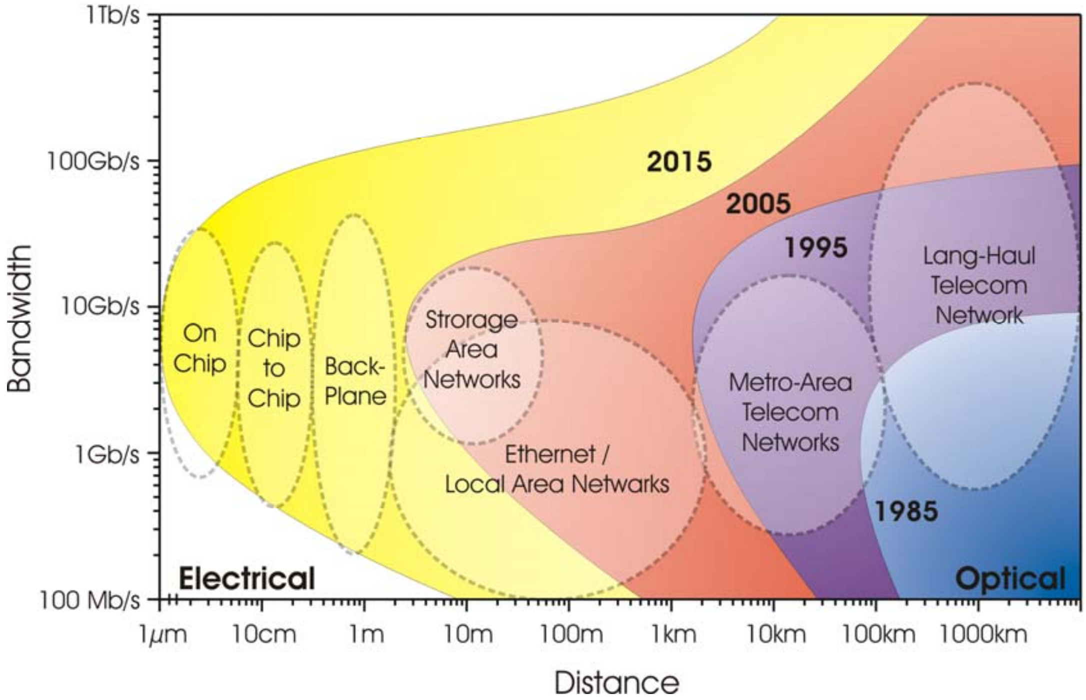

Figure 4: Historical development of the application of electrical and optical data processing [4]. The coloured regions indicate the acquisition of optical data transfer. As a consequence of the big advantages optical data transfer is inevitable penetrating the telecommunication sector deeper every year.

Optical data transfer requires laser light. These laser devices are usually made out of III/V compound semiconductors. So far the application of optical data processing always involves expensive optical transceiver and/or a precise alignment between the Si-based chip and the III/V-light diode using hybrid integration scenarios.

Silicon Photonics wants to combine the advantages of optical data processing with the high technology know-how of Si-based integrated circuits.

An efficient light source integrated on Si substrate could provide chip-to-chip or even on-chip communication within high-bandwidth data transfer, no signal latency and without the need of heat dissipation. The realisation of optoelectronic integrated circuits (OEICs) would tremendously increase the functionality of Si-microelectronics and revolutionise future chip design.

One of the main challenges for Si-Photonics is the integration of a laser on Si substrates. Si is a poor light emitter due to its indirect band gap. Light emission is phonon-mediated and has a very low internal quantum efficiency of about 10^{-6}. Furthermore, free carrier absorption hinders population inversion essential for stimulated light emission and material gain, respectively, as well as Auger recombination reduces the emitted photon density, see figure 5.

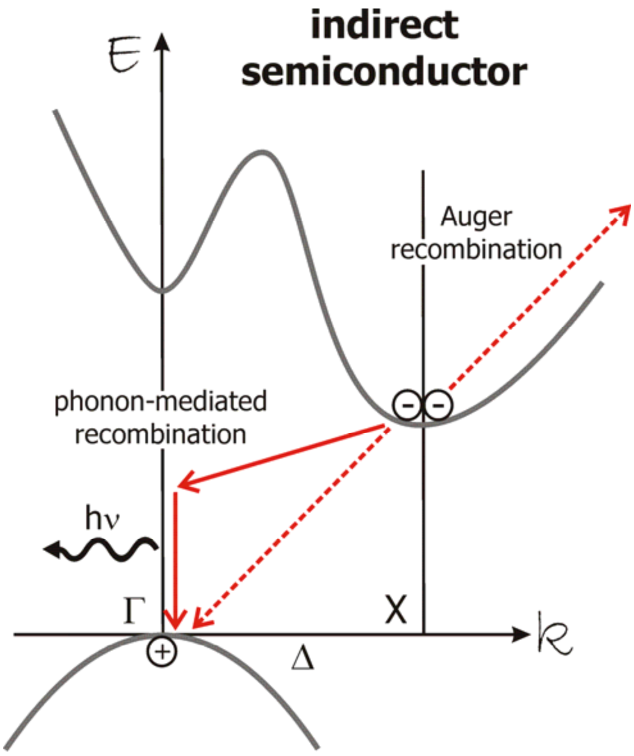

Figure 5: Schematic drawing of the indirect band structure of Silicon. Excited carriers can combine by phonon-mediated recombinations or Auger recombination, which are both indicated by arrows.

However, a “true” monolithic integration of a laser material onto a Si chip would bypass expensive production cost, offer a wider spectrum of applications and allows for sophisticated miniaturisation of optoelectronic integrated circuits (OEICs) as compared to hybrid integration scenarios.

Concepts for the integration of a laser light source

Since early 1990s, researchers have been exploring novel techniques, e.g. Si-nanocrystals [6] or Er-doped Si [7], to circumvent the weak luminescence efficiency of Silicon, but even intense luminescence was found to be very difficult to achieve yet. The first optically pumped all-Silicon based laser was demonstrated by stimulated Raman scattering in Silicon waveguides in 2004 [8] followed by the demonstration of a continuous wave (cw) laser in 2005 [9]. Although this achievement enables novel applications including optical amplifiers and wavelength converters integrated on the chip, there is still the basic necessity of an optical pump source for the rather inefficient non-linear Raman process.

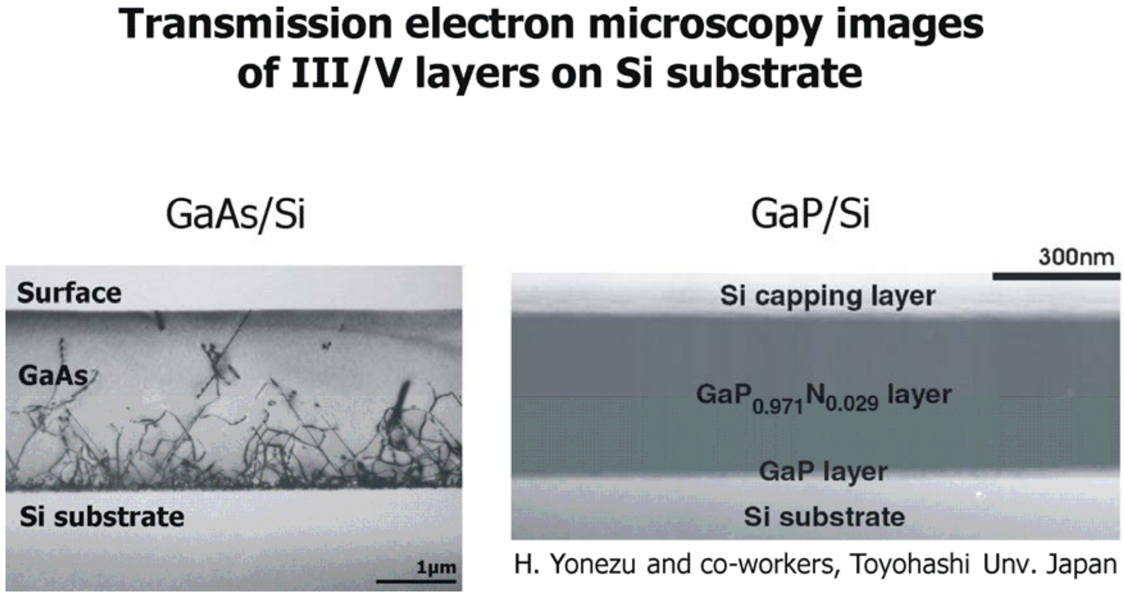

Figure 6: Transmission electron microscopy images. Caused by the large lattice mismatched a high density of misfit dislocation is formed in the GaAs layer grown on Silicon. In contrast GaP/GaNP sequences can be grown on Silicon without the generation of any threading dislocations [11].

Another approach to realise a Si-based electrical injection laser is heteroepitaxy. Standard direct band gap III-V compound semiconductors like GaAs (gallium arsenide) [10] or InP (indium phosphide) are deposited on Si-substrates to merge their sophisticated optical properties with Si. Because of the large lattice mismatch of these standard materials to Si, high densities of threading dislocations are formed in the epitaxial III-V film, see figure 6 (left micrograph).
This obstacle becomes obviously in figure 7, which summarises the energy gap plotted versus the lattice constant of the most common III-V semiconductors in comparison to Si. GaAs as well as InP have a lattice constant larger by more than 4% than that of Si. The technological challenge is to optimise the epitaxial growth conditions to suppress the formation of dislocations in the complete III-V layer. Although III-V laser diodes were realised [10], the high densities of misfit dislocations are still preventing any long-term stable lasing operation of optical device structures until now.

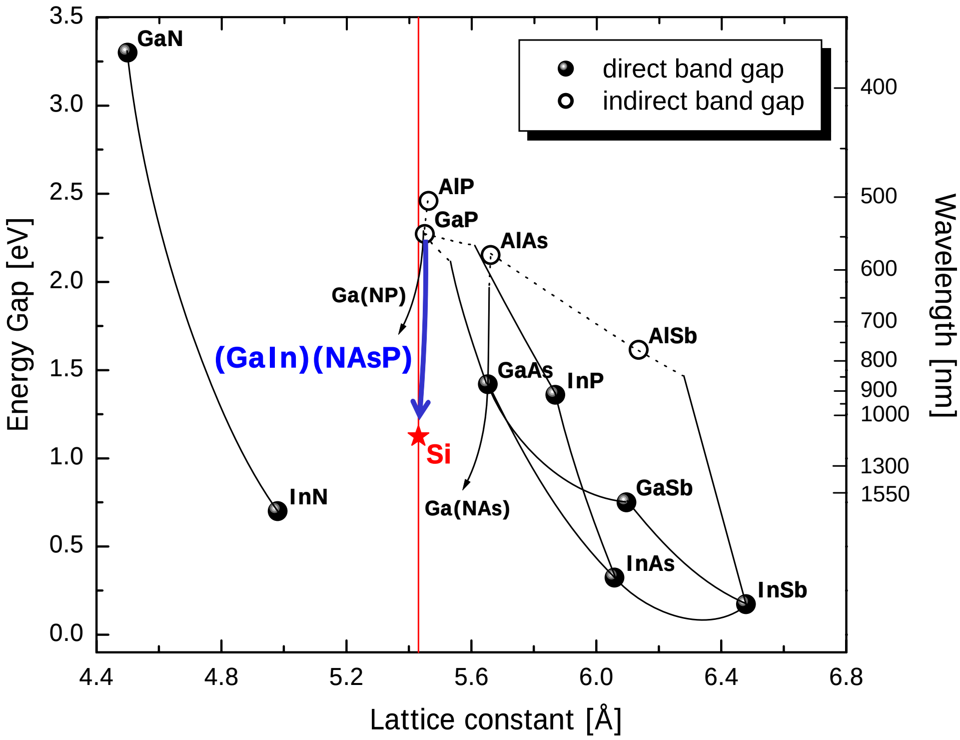

Figure 7: Energy gap versus the lattice constant of the most common III-V semiconductors in comparison to Si. The indirect semiconductor GaP has a lattice constant almost equal to Si, which allows for a dislocation free growth of GaP layer on Si-substrate.

A view at the lattice constants of different III-V compound semiconductors plotted in figure 7 reveals, that the indirect semiconductor GaP (gallium phosphide) has a lattice constant almost equal to that of Si. In addition, the ternary material system Ga(NP) (gallium nitride phosphide) can be grown lattice matched to Si-substrate with a N-content of only two percent. Prof. Hiroo Yonezu and co-workers of the University of Toyohashi in Japan demonstrated the heteroepitaxial growth of Ga(NP)/GaP layer sequences on Si-substrates with high structural perfection and without the formation of any misfit dislocations and antiphase domains [11].

Based on this fact the research activity at the Material Sciences Center [internet link] of the Philipps-University Marburg (Germany) followed a new concept to integrate a laser material on Silicon: **the development of a novel direct band gap material, which can be grown lattice-matched to GaP and therefore transferred in a straight forward way to Si-substrates.**

The incorporation of Indium (In), Arsenic (As) as well as Nitrogen (N) enables the modification of the band structure in order to change the indirect band gap to a direct one, as a basic necessity for high material gain and lasing activity. The combination of N with In and/or As allows for the essential adjustment of the lattice constant of the pentернary compound semiconductor (GaIn)(NAsP) to the lattice constant of GaP, see also figure 7. The challenge is to find the right material composition of (GaIn)(NAsP), which facilitates the pseudomorphic growth of high quality films on GaP-substrate and reveals a direct band structure and a high luminescence efficiency, respectively, at the same time.

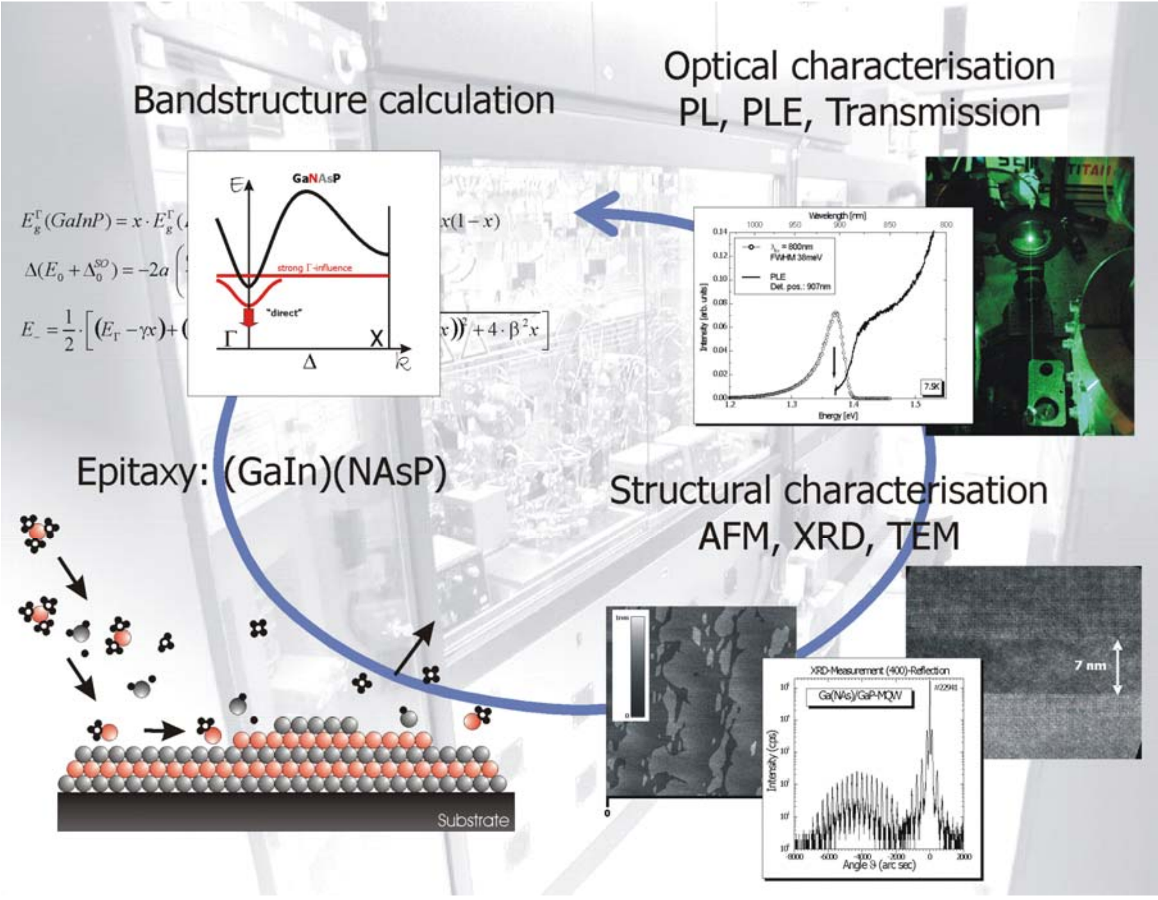

Figure 8: Iterative operation loop of fundamental band structure calculation, crystal growth via metal organic vapour phase epitaxy (MOVPE), structural as well as optical characterisation and final verification of the experimental results with the elemental theory.

Since 2001 the group at the Material Sciences Center has established a profound knowledge in the epitaxial growth of various material systems on GaP-substrates [12-16]. In iterative loops of fundamental band structure calculation, crystal growth by metal organic vapour phase epitaxy (MOVPE), structural as well as optical characterisation and a final verification of the experimental results by theory, all entering into the next iteration loop, diverse material compositions based on GaP were investigated, see figure 8.

After intensive study of various compound material systems like (GaIn)(NAs), (GaIn)(NAsP) and Ga(NAsP) the novel As-rich dilute nitride material system Ga(NAsP) was introduced, which can be growth pseudomorphically strained on GaP-substrate and reveals a direct band structure and a high luminescence efficiency [13-16], see figure 9.

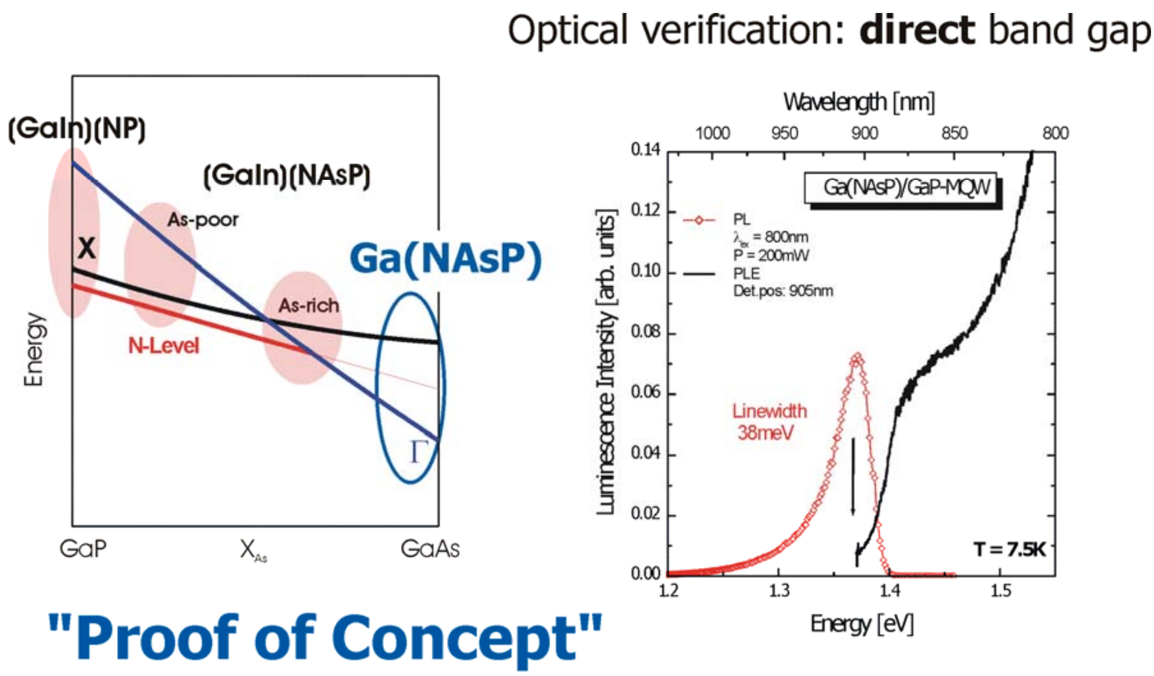

Figure 9: In accordance with fundamental band structure calculation the compound material system Ga(NAsP) grown on GaP-substrate reveals a pronounced direct band gap proven by spectroscopic investigation (Excitation photoluminescence measurements).

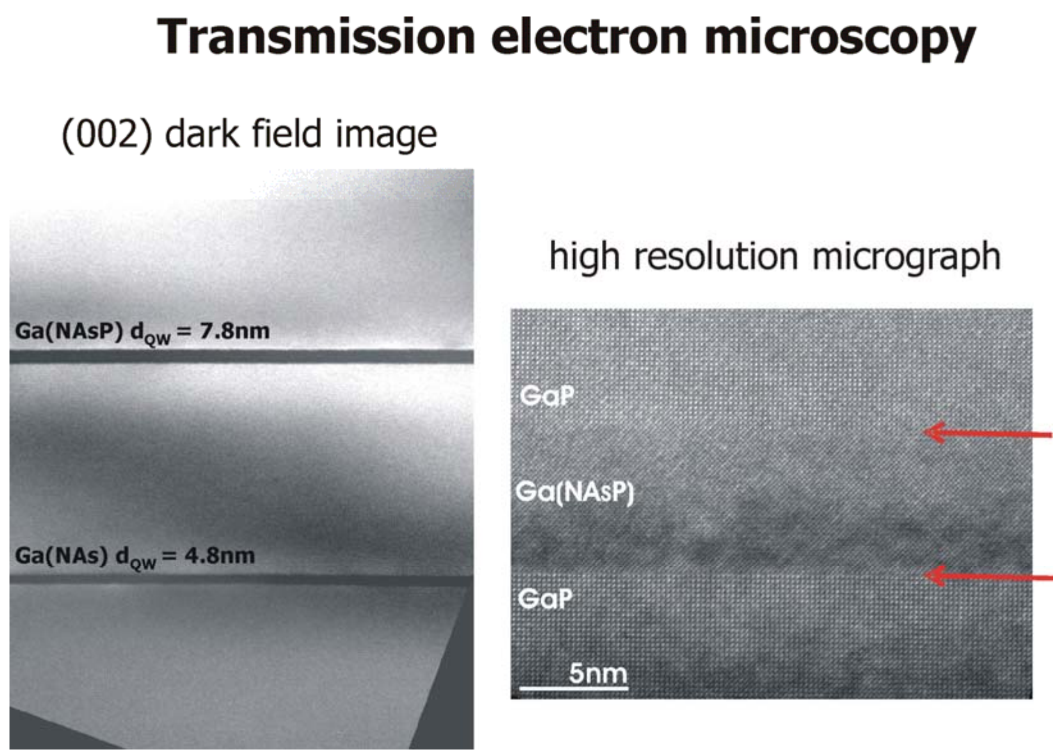

Figure 9: Dark field und high resolution transmission electron micrographs of Ga(N(P)As) quantum wells grown on GaP-substrate.

The high structural crystal quality and the absence of any misfit dislocation was proven by transmission electron microscopy, see figure 9. Only for the As-rich regime this novel material system exhibits a direct electronic band structure, whereas the unique band gap formation caused by the incorporation of a few percent of N leads to a strong reduction of the band gap energy and hence to more pronounced direct band gap of the quaternary material system [14]. Already thin multi-quantum-well layers of Ga(NAsP) act as an excellent light emitter. In addition, first gain measurements emphasise materials properties comparable to standard III/V material systems applied in commercial laser diodes [17].

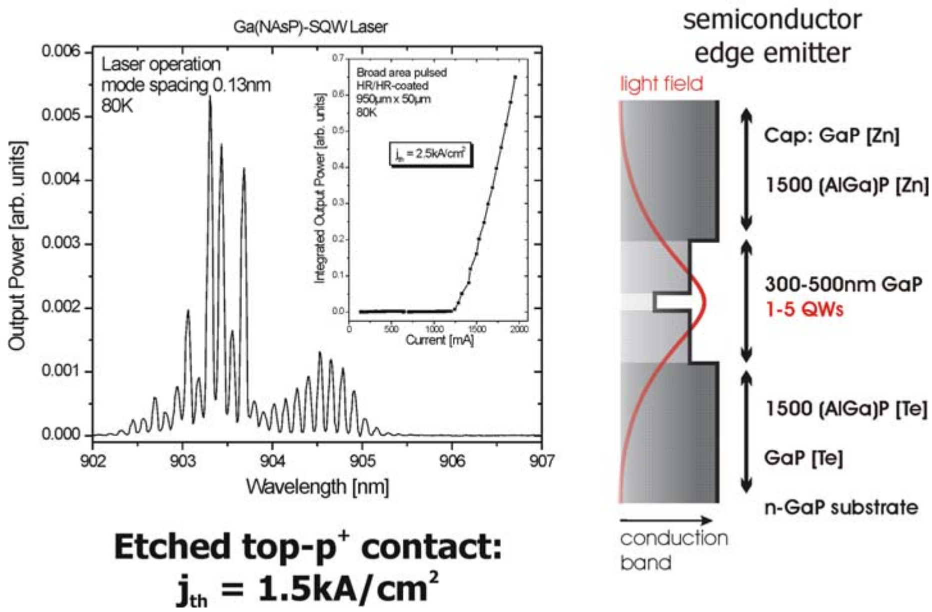

Figure 10: Emission spectrum of an electrically pumped Ga(NAsP)/GaP-SQW laser structure under pulsed operation at 80 K. The inset shows the threshold type output characteristic as a function of current. The SQW is embedded in a n/p doped (AlGa)P separate confinement hetero structure [13].

The first proof of electrically injected lasing activity of Ga(NAsP)-device structures at low temperature [13] as well as near room temperature [15] at a very early stage of material development underlines the potential of this novel material system for various device applications. The findings for the growth on GaP-substrate can be transferred in a straight forward way also for the deposition on Si-substrate.

This concept will lead to a real monolithic integration of III-V-based optoelectronics and Si-based microelectronics in the near future. The whole impact of such an innovative device concept is hard to predict but without any doubt revolutionary for the entire information technology.

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