Dr. Christoph Deutsch

Novel Semiconductor Materials and Growth-related Asymmetries in Terahertz Quantum Cascade Lasers

Supervisor: Karl Unterrainer

ABSTRACT

Terahertz quantum cascade lasers (THz QCLs) are amongst the most promising sources for terahertz radiation. These semiconductor lasers are compact, efficient, and emit high optical output powers in the order of several milliwatts. However, operating temperatures of these devices are still limited to a maximum of 200~K, requiring elaborate cryogenic cooling and hampering a widespread employment in real-world applications. The first demonstration in 2002 was followed by a rapid development. In recent years though, the progress has slowed down and only little improvements have been achieved. This trend strongly suggests to reconsider the basic concept and to go into new directions.

THz QCLs are almost exclusively fabricated in the established GaAs/AlGaAs material system. The reason is a arbitrarily adjustable conduction band offset. However, it is also known that GaAs/AlGaAs exhibits certain drawbacks for QCL operation because of other material parameters.

Therefore, InGaAs/InAlAs is used for mid-infrared QCLs, which are closely related devices. Amongst others, this material system has the advantage of a lower effective electron mass. A further difference is the higher conduction band offset, which is in turn a disadvantage for THz QCLs:

Smallest deviations of the epitaxial growth from the nominal structure have serious consequences on the transport and lasing performance eventually.

The first goal of this PhD thesis was to investigate the advantages and disadvantages of a novel material system: InGaAs/GaAsSb lattice-matched to an InP substrate. The use of a GaAsSb instead of an InAlAs barrier alleviates the growth difficulty. The GaAsSb barrier exhibits a lower conduction band offset and a lower effective electron mass. This allows the employment of thicker barriers in the active region. This material advantage could be exploited and InGaAs/GaAsSb THz QCLs with a maximum operating temperature of 142 K were realized - a new record for InP/InGaAs-based devices.

New material systems have problems to keep up with established systems in terms of growth quality. THz QCLs impose high demands on it: atomically sharp interfaces, low background doping density, and stable, latticed-matched growth conditions over several hours. Interfaces, however, are an issue for InGaAs/GaAsSb heterostructures because of the group V material mixing (As, Sb). It results in a pronounced interface asymmetry between both sides of the GaAsSb barrier, depending on the growth direction. Within this work, a novel concept to investigate such growth-related asymmetries was introduced: Symmetric active regions allow to reveal and quantify the influence of the growth direction by switching the applied bias polarity. The comparison between both bias polarities is extremely significant and a favorable operating direction (electron transport in growth direction) could be determined. QCLs are - despite the lack of a scientific basis - traditionally operated in the opposite operating direction (electron transport against growth direction). Based on this surprising results, the study was extended on the established material systems GaAs/AlGaAs and InGaAs/InAlAs. By using symmetric GaAs/AlGaAs THz QCLs, a significant performance asymmetry could be ascribed to the migration of dopant atoms during growth. In contrast to interfaces, this asymmetry can be manipulated or even compensated by shifting the doping profile. Through the comparison of different doping profiles, indications for interface asymmetry were also here observed.

Consequently, the best lasing performance for the GaAs/AlGaAs material system was also achieved in the non-conventional, reverse operating direction. Using this knowledge, the group's record (TU Vienna) could be improved to a maximum operating temperature of 173 K. Finally, growth

asymmetries were investigated in the InGaAs/InAlAs material system, yielding another sensational result. Once more, the own record of 142 K for InP/InGaAs-based THz QCLs could be outdone.

In a collaboration with the Princeton University, investigations on symmetric mid-infrared QCL structures were carried out. Likewise, a significant influence of the growth direction was observed, which promises an additional potential for optimization of the already highly mature mid-infrared QCLs.