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Nanoscale transport and photonic confinement in terahertz quantum cascade lasers

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ABSTRACT:

The terahertz spectral region is of fundamental importance in many fields of science and for a lot of practical applications, but it is technologically difficult to cover with common light sources. Terahertz quantum cascade lasers (QCLs) have been developed as compact and efficient sources of coherent terahertz radiation. QCLs are optoelectronic devices based on a quantum engineered semiconductor heterostructure gain medium that is integrated into an optical cavity, which is suitable for the particular emission frequency, covering a range up to the far-infrared or terahertz spectral region. The layered semiconductor structure in the active region forms a periodic series of quantum wells, which confines the electrons perpendicular to the interfaces, and results in a set of discrete electronic subbands. The stimulated emission of terahertz radiation in these unipolar devices originates from optical intersubband transitions between dedicated upper and lower laser levels, where a population inversion is conveniently obtained by electrical pumping through applying a defined bias voltage. A major drawback of state-of-the-art terahertz QCLs is their limitation to an operation at cryogenic temperatures. A promising strategy to overcome this limitation is to introduce an additional quantum mechanical confinement in the in-plane direction, which results in longer nonradiative upper-state lifetimes, by incorporating semiconductor nanowires. In this thesis, the feasibility of nanowire-based devices was systematically investigated by gradually scaling micropillar-based photonic crystal lasers to shrinking diameters, forming photonic metamaterials. Subwavelength micropillar array terahertz lasers operating in the effective medium regime of the photonic band structure were designed and experimentally demonstrated. The experimental results showed that optical losses occurring in the material filling up the space between the micropillars significantly increase the required filling factor to achieve lasing in the effective medium regime. The employed theoretical model predicts that by avoiding these optical losses, for example using a free standing array of nanowires or micropillars, rather low filling factors provide sufficient optical gain for lasing, which results from the confinement of the optical mode energy in the high index semiconductor medium. The demonstrated results constitute an important milestone towards the realization of nanowire terahertz lasers, which have the potential to enable an operation using thermoelectric cooling, or even up to room-temperature. Another possibility to improve the performance of standard GaAs/AlGaAs terahertz QCLs is the transition to InGaAs-based material systems exhibiting favorable material properties in form of a lower effective electron mass. A particularly intriguing unsolved question regarding this matter is the identification of the best suited barrier material, which especially differ in the resulting conduction band offset. In general, a direct comparison of active region designs using different material systems is problematic. In this work, a systematic comparison was performed by quantum engineering equivalent active region designs utilizing the InGaAs/InAlAs, InGaAs/InAlGaAs, and InGaAs/GaAsSb material systems with an automated genetic algorithm. The experimental realization and characterization of these devices showed that the tendency to very thin barriers for large conduction band offsets poses no evident limitation in terms of the resulting device performance. This motivates a further investigation of the well-established InGaAs/InAlAs material system for designing terahertz QCLs, and its potential to outperform the standard GaAs/AlGaAs system. A limiting factor for the performance of terahertz QCLs is the fact that the large number of semiconductor interfaces drastically reduces the thermal conductivity perpendicular to the interfaces. This results in case of a significant amount of dissipated electrical energy, for large duty cycles or continuous-wave operation, in a considerable temperature gradient between the heat sink and the top of the active region. Here, a thermal characterization technique is demonstrated that uses the top metal waveguide layer as a temperature sensor in order to measure the lattice temperature in the active region. The results show that the lattice temperature in the active region can be conveniently monitored during operation using an all-electrical measurement technique, and the thermal properties can be extracted using the measured temperature data in combination with a simple thermal model of the device. A comparison of a GaAs-based and an InGaAs-based active region indicates a lower thermal conductivity of the latter. The investigation of a symmetric active region, which can be operated in both bias directions further revealed a significant influence of the operating direction on the thermal properties, with a smaller effective thermal resistance for an electron flow towards the heat sink. The demonstrated technique greatly simplifies the measurement of the active region temperature, which is not only important in terms of the thermal characterization, but also relevant for the controlled tuning of the emission wavelength as well as a thermal stabilization. The continuing progress towards on-chip terahertz systems implies the integration not only of terahertz sources, but also detector structures. A particularly promising approach in this context is the generation of photocurrents in quantum cascade structures illuminated by terahertz radiation. As an additional part of this thesis, the non-equilibrium Green's function technique was used for evaluating photocurrent effects in quantum cascade structures. The results show that the investigated active region designs can be operated in a detector mode, where the detected frequency is tuned by the applied electric field in resonance with the emission frequency of the lasing structure. The combination of these alternative functions of a single quantum cascade structure into complex photonic integrated circuits can be utilized for the on-chip generation, modulation, and detection of terahertz light, which is of profound relevance for many practical applications.