

1.3 Semiconductor Spectroscopy

The research activities of this department cover elementary excitations (photons, electrons, and spins) and their control by surface acoustic waves (SAWs), the optical properties of wide-gap group-III nitride films, hetero-, and nanostructures, the design and the optical as well as transport properties of quantum-cascade lasers, the magneto-transport properties of curved two-dimensional electron gases, the spin-injection efficiency of ferromagnet-semiconductor hybrid structures and their magneto-optical as well as magneto-transport properties, and the quantum transport theory for carriers and spins.

Although extensive research on nanostructures has led to the discovery of a number of efficient ways to confine carriers in reduced dimensions, little has been done to make use of the unique properties of such systems which are realized by coupling nanostructures by means of the controllable carrier transfer. We have demonstrated a novel approach for the controllable transfer of electrons and holes from a semiconductor quantum well to an embedded quantum dot using the moving piezoelectric potential modulation induced by an acoustic phonon [O. D. D. Couto *et al.*, *Nature Photon.* **3**, 645 (2009)]. This moving potential not only transfers carriers between the quantum well and an array of quantum dots, but can also control their capture and recombination in discrete quantum dot states within the array. This feature is used to demonstrate a high-frequency, single-photon source with tunable emission energy.

We have realized GaAs/(Al,Ga)As terahertz (THz) quantum-cascade lasers (QCLs) based on alternating photon and longitudinal optical (LO) phonon-assisted transitions between quasi-minibands [M. Wienold *et al.*, *Electron. Lett.* **45**, 1030 (2009)]. The design is optimized for low threshold current densities and low operating voltages, resulting in reduced ohmic heating during continuous-wave (CW) operation. The QCLs exhibit lasing over a broad range of frequencies from 2.91 to 3.21 THz. Using single-plasmon waveguides, pulsed operation up to 114 K and CW operation up to 65 K has been achieved. The rather broad emission range of about 10% compared to the central frequency may be an attractive feature of such a design for tunable distributed-feedback or external-cavity QCLs.

With regard to GaN nanowires, we have investigated the low-temperature photoluminescence spectra of GaN nanowires grown catalyst-free on Si(111) [O. Brandt *et al.*, *Phys. Rev. B* **80**, in press (2009)]. For single nanowires dispersed on Si(111), we observe excitonic transitions with line widths below 300 μeV and at energies clearly above the donor-bound exciton in the bulk, which are attributed to donor-bound excitons close to the surface. The observed spectra suggest that point defects and impurities are driven to the nanowire sidewalls during growth, resulting in an overall crystal quality even higher than that of state-of-the-art homoepitaxial layers. The broadening of about 3 meV observed for the nanowire ensemble is shown to be a natural consequence of the energy dispersion of bound-exciton states as a function of their distance from the surface.

We have demonstrated that epitaxial films of the phase-change material Ge-Sb-Te (GST)

with a composition close to $\text{Ge}_2\text{Sb}_2\text{Te}_5$ can be switched between the crystalline and amorphous phase and recrystallized again. [W. Braun *et al.*, Appl. Phys. Lett. **94**, 041902 (2009)]. As-grown, amorphized, and recrystallized locations have been investigated by Raman spectroscopy. The Raman spectra for the different locations on the GST films reveal clear signatures corresponding to GST in the three different phases, where the amorphized and recrystallized phases are achieved by laser switching.

The quantum Hall effect has been investigated in a high-mobility two-dimensional electron gas on the surface of a cylinder [K.-J. Friedland *et al.*, Phys. Rev. B **79**, 125320 (2009)]. This special topology leads to a spatially varying filling factor along the current path. The resulting inhomogeneous current-density distribution gives rise to additional features in the magnetotransport data such as resistance asymmetry and modified longitudinal resistances. We have experimentally demonstrated that the asymmetry relations satisfied in the integer filling factor regime are valid also in the transition regime to noninteger filling factors, thereby suggesting a more general form of these asymmetry relations.

Based on the nonequilibrium Green's function technique, a unified theory has been developed that covers quantum transport and quantum diffusion in bulk semiconductors on the same footing [P. Kleinert, Phys. Rev. E **79**, 051107 (2009)]. This approach, which is applicable to transport via extended and localized states, extends previous semi-phenomenological studies. Even for the unified treatment of quantum transport and quantum diffusion in homogeneous systems, all quasimomenta of the carrier distribution function are shown to be present and to fulfill their specific function. To demonstrate the existence of robust macroscopic transport effects that have a true double-time character, a phononless steady-state current is identified appearing only beyond the generalized Kadanoff-Baym ansatz.

In a joint effort with the Epitaxy research group, strain-dictated epitaxial orientations in MnAs layers on the A and B surfaces of GaAs(113) have been investigated by comparing the growth using solid-phase epitaxy with the one by molecular-beam epitaxy [Y. Takagaki *et al.*, Phys. Rev. B **80**, 014116 (2009)]. For the layer on GaAs(113)A grown by means of solid-phase epitaxy, a drastically different crystalline orientation and surface morphology have been found, while smooth $(1\bar{1}00)$ - or $(1\bar{1}01)$ -oriented layers are otherwise obtained. We have shown that the $(21\bar{3}1)$ orientation is realized in the unconventional layer due to the minimization of the strain energy. The layer consists of structural domains associated with in-plane inclinations of the c -axis of MnAs by about $\pm 42^\circ$ from the $[33\bar{2}]$ direction of the substrate, giving rise to a polycrystalline surface morphology. The combination of coexisting crystal orientations is found to lack some reflection symmetries as a consequence of an asymmetry in the bonding energy.