Features of lateral and vertical transport of electrons in quantum heterostructures based on group III nitrides.

Dissertation for the Candidate (PhD) degree in Physics
and Mathematics in specialty Solid State Physics

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The work is related to electron transport in single- and double-barrier semiconductor quantum heterostructures (HS) based on group-III nitrides ($Al_xGa_{1-x}N$/GaN). The essential feature of nitride HS is their ability to form a conduction channel with the two-dimensional electron gas (2DEG) confined in the quantum well at the heterointerface, as a result of strong spontaneous and piezoelectric polarization. Physical phenomena that occur in such nitride heterostructures in high electric and magnetic fields at cryogenic and room temperatures were experimentally studied to obtain the features of charge carriers' recombination and transfer in the conduction channel with 2DEG. Additionally, theoretical modeling and numerical calculations of the energy band structure and electronic properties of the studied HS were conducted for analysis and interpretation of experimental data.

The investigated $Al_xGa_{1-x}N$/GaN structures with Al content in the range x = 0.25 - 1.0 and different layers design (the transistor-like structures with GaN buffer and AlGaN barrier layers; the resonant-tunneling diode structures with AlN/GaN/AlN double barriers and quantum well layers) were grown by MOCVD (transistor structures) and MBE (diode structures) techniques on Al_2O_3 and SiC substrates. The research methods include: current-voltage and capacitance-voltage characterization; magnetotransport measurements (temperatures of 0.3-4.2 K, magnetic fields up to 10T); optical measurements, including photoluminescence (PL) spectroscopy in the energy range 2.6-3.8 eV at temperatures of 4.2 K / 300 K and cathodoluminescence spectroscopy; noise spectroscopy.

Studying photoluminescence in AlGaN/GaN heterostructures with modulation-doped (Si-doped) and undoped AlGaN barriers, the effect of the PL spectral transformation was revealed. The band at 3.46-3.3 eV, associated with electron-hole recombination of the 2DEG at the AlGaN–GaN heterointerface, in modulation-doped HS has disappeared. Instead, together with the enhanced band-edge PL at 3.49 eV, an intense band at 3.3-2.7 eV, attributed to recombination of donor-acceptor pairs with deep-level acceptor centers caused by the doping, has appeared. The resultant PL modification caused by modulation doping of AlGaN barrier is established and depends on the doping density and on the position of the doping layer with respect to the AlGaN/GaN interface.

Studying magnetotransport in AlGaN/GaN heterostructures with a different degree of quantum confinement (which is connected with different design of HS: varying of Al content in the AlGaN barrier ~25-33%, barrier thickness ~20 – 30 nm, as well as introducing additional AlN layer), the band edge effective mass of the 2DEG formed at the AlGaN–GaN heterointerface was deduced to be equal to $(0.2\pm0.01)m_0$. It is found that from all factors affecting the 2DEG effective mass value (including the sheet carrier density, conduction band nonparabolocity, polaron effect, magnetic field effect, and the electron wave-function hybridization), the hybridization of the wave-function plays the dominant role and the electron wave-function penetration into the barrier layer should be taken into account.

In the study of lateral transport in the transistor-like AlGaN/GaN heterostructures, the effects of self-heating of the 2DEG conducting channel and strong dependence on conduction channel's size, GaN buffer thickness, and substrate material (sapphire or SiC) were demonstrated. Using noise spectroscopy, the activation energy of the traps influencing the transport in AlGaN/GaN 2DEG channel was determined. Depth-resolved cathodoluminescence spectra revealed that these traps are associated with defect states in the GaN buffer layer. Additionally, the positive effect of small doses of γ-irradiation by ^{60}Co on the improvement of the characteristics of AlGaN/GaN transistor-like HS (namely, structural defect ordering and improvement in the mobility of the electrons in the 2DEG channel) has been confirmed.

In the study of vertical transport in the double-barrier resonant tunneling diodes (DB-RTD) based on AlN/GaN/AlN HS (using current-voltage and capacitance-voltage characterization), a complex non-linear character of the tunneling processes caused by the interplay of external and internal built-in electrical fields in the AlN barriers and GaN quantum well was shown. Numerical simulations of the potential profile of the given structures, using a model based on real-time Green's functions, have been performed taking into account polarization effects at the AlN/GaN interfaces. The reasons for a current instability and nonlinearity of DB-RTD characteristics associated with the trapping the electrons onto interfacial and dislocation states near the active region of the HS, were determined. Possible ways to improve characteristics of such HS are reducing the asymmetry of the potential profile around the double barrier region and minimizing the density of defects related to dislocations, which can serve as traps for charge carriers.

List of publications of A. Naumov associated with the PhD thesis

Journal publications

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