Design considerations for GaN/AlN based unipolar (opto-)electronic devices, and interface quality aspects

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Abstract: We describe the theoretical and experimental studies of GaN/AlGaN based resonant tunnelling diodes, and in particular analyse the effects and typical values of interface roughness, and then discuss the implications of these, realistic material quality parameters on performance of unipolar optoelectronic devices.

The AlGaN/GaN material system has been proposed as a highly promising alternative to more conventional III–V systems from the perspective of various optoelectronic devices, including quantum cascade lasers operating from mid-infrared to THz range, photodetectors and electronic devices like resonant tunnelling diodes. In the longer wavelength range the high LO-phonon energy (92 meV) in GaN is expected to significantly reduce the thermal degradation effects, coming from non-radiative phonon-assisted transitions between active laser states, which could potentially allow laser emission at higher THz frequencies, and also higher temperature operation [1]. In the shorter, mid-infrared range, the high conduction band offset between AlN and GaN (~2 eV) can be exploited to comfortably confine subbands with separations required for laser emission at 1.55 μm [2], and could additionally reduce leakage currents, enabling high temperature operation. However, while electroluminescence has been demonstrated, there seems to be a lack of a successful demonstration of lasing in these devices.

An accurate description and detailed understanding of electron transport in AlGaN/GaN heterostructures is critical for optimizing their performance, and ultimately realizing high-quality optoelectronic devices. Resonant tunnelling diodes (RTDs) are interesting devices in their own right, and also the simplest devices in which vertical tunneling and scattering transport can be extensively investigated, both experimentally and theoretically: the experience might then be transferred to the design of more complicated, optoelectronic devices. With these aims we have investigated electron transport in epitaxially grown nitride-based resonant tunneling diodes (RTDs), as well as in superlattice-type sequential tunneling devices [3]. The density-matrix model was developed, and shown to be able to reproduce the experimentally measured current–voltage characteristics, with the dephasing terms in the model calculated from semi-classical scattering rates. Scattering-induced broadening effects are found to have a significant influence on the predicted / experimental performance. In particular, the interface roughness parameters have a very strong influence on current magnitude, peak-to-valley ratios and misalignment features, up to the extent of being able to destroy the negative differential resistance in RTDs. Furthermore, the characteristics of sequential tunneling devices are dominated by a parasitic current, most likely caused by dislocations. Overall, an excellent agreement between the simulated and experimentally measured tunneling current-bias dependence is demonstrated. The analysis of the scattering effects, contact doping and growth quality on electron transport highlights critical optimization parameters for the development of III–nitride unipolar electronic and optoelectronic devices.

Investigation of AlGaN quantum cascade laser structures, also performed by the density matrix method, shows that a realistic level of interface roughness will significantly degrade the gain and useful operating temperature of some previous designs [4]. These can be improved by a structure optimization, based on a genetic algorithm [4], however it is likely that further improvements of the material quality are essential for the III-nitride optoelectronic devices to demonstrate their full potential.

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