Growth, properties, and optoelectronic applications of III-As and III-N nanowires

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The growth of compound semiconductors in the form of nanowires offers the advantage that strain can elastically relax at the free sidewalls. Thus, in heteroepitaxy the critical thickness at which dislocations form is increased and it is even infinite for sufficiently thin nanowires. Consequently, dissimilar materials can be combined in high structural quality. Possibly the most relevant implementation of this conceptual advantage is the monolithic integration of compound semiconductors on Si substrates. Progress in this field could lead to efficient light emitters on the established platform for complementary-metal-oxide-semiconductor (CMOS) technology, which in turn could be a decisive step towards chip-to-chip or on-chip optical interconnects that are under consideration for future generations of computer processors.

In our group, both III-As and III-N nanowires are grown by molecular beam epitaxy on Si substrates, and no external material is employed as catalyst or mask to induce the formation of nanowires. In particular, the growth of GaAs nanowires is mediated by Ga droplets at their tips. However, in this growth mode the standard n-type dopant Si is incorporated on both the Ga and As sub-lattices, resulting in auto-compensation. In order to achieve n-type conductivity, we have devised a shell doping scheme. Si is provided only during the growth of a GaAs shell around an undoped GaAs core and incorporated only on the Ga sub-lattice [1]. In a similar way, we have fabricated core-shell (In,Ga)As/GaAs quantum wells. By combining the two approaches, we have grown and processed light-emitting diodes based on core-shell nanowires on Si substrates that emit electroluminescence at room temperature.

In axial nanowire superlattices of two materials A and B, the elastic relaxation of strain mentioned at the beginning takes place in both materials. Thus, compared to planar superlattices on a substrate made of material A, in nanowires material B is less strained but material A is more strained. It is intuitively clear that this effect depends on the ratio of the segment thicknesses. By calculations and experiments with (In,Ga)N/GaN nanowire heterostructures, we have demonstrated that under certain conditions the strain state of the (In,Ga)N quantum wells depends linearly on the segment thickness ratio. Therefore, strain can be tuned in a wide range without any changes in chemical composition.

The increase of the critical thickness is particularly attractive for materials for which bulk substrates are not readily available, as it is the case for (In,Ga)N. This material is very promising for solar water splitting, a technology that could form the basis for a sustainable hydrogen economy. However, only layers much thicker than the critical thickness of (In,Ga)N on all conventional substrates would capture light effectively. In contrast, long (In,Ga)N nanowires can be grown in high crystal quality. Moreover, charge carriers have to migrate in nanowires only a short distance to reach the surface, and the large surface-to-volume ratio is associated with many sites for catalytic reactions. We have investigated the photoelectrochemical properties of (In,Ga)N nanowires and have obtained very encouraging results.

[1] E. Dimakis, M. Ramsteiner, A. Tahraoui, H. Riechert, and L. Geelhaar, Nano Research **5**, 796 (2012).