Controlling heterostructures with atomic precision in III-V nanowires using microheaters in an in-situ TEM

Mr. Christopher Røhl Yskes Andersen[1,2], Mr. Marcus Tornberg[3,4,5], Mr. Sebastian Lehmann[4,5], Mr. Daniel Jacobsson[3,4], Prof. Jonas Johansson[4,5], Prof. Kimberly A. Dick[3,4,5], Prof. Kristian S. Mølhave[1]

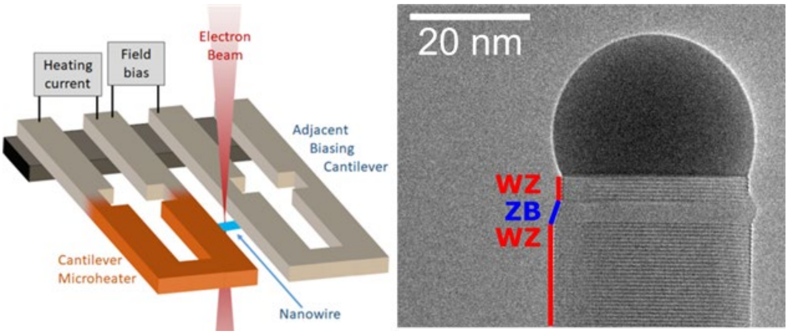
[1]DTU Nanolab, Technical University of Denmark, Kgs. Lyngby, Denmark, [2]Quantum DTU, Technical University of Denmark, Kgs. Lyngby, Denmark, [3]nCHREM, Lund University, Lund, Sweden, [4]NanoLund, Lund University, Lund, Sweden, [5]Solid State Physics, Lund Uni., Lund, , Lund, Sweden

Precision in heterostructure control within III-V nanowires is essential for the advancement of future technologies, especially quantum computing and quantum internet. The ability to embed one crystal phase, e.g., zincblende, within another, e.g., wurtzite, can be used to determine the optical and electrical properties of so-called crystal phase quantum dots. This crystal phase engineering offers a sharp transition between phases, superior to compositional quantum dots, but its control remains challenging within traditional ex-situ growth environments. Integrated electron microscopy with gas handling capabilities offers a unique in-situ perspective, revealing the dynamics of crystal phase formation and the parameters influencing it. Our research study is focused on how changing the growth conditions can be used to enable atomically precise crystal phase control. We also look into the growth dynamics and the commonly assumed control parameter: the contact angle, to unravel its actual impact on crystal phase determination in GaAs nanowires.

We use a cantilever based microheater system for GaAs Metalorganic Vapor Phase Epitaxy (MOVPE) growth within a Transmission Electron Microscope (TEM) as depicted in the figure to the left. This setup enables us to map the crystal phase formation at different growth conditions, specifically varying temperature and group V precursor flow. Instantaneous adjustments in temperature and precursor flow allow for the real-time analysis of the dependencies between these growth parameters and the phase transitions as illustrated in the figure to the right. Additionally, we introduce a field perturbation technique to the catalytic droplet to decouple its shape from the underlying growth conditions, further investigating the mechanisms driving the phase formation.

Our findings reveal that crystal phase transitions can be controlled with atomic precision using temperature shift in-situ. The cantilever-based microheaters offer rapid temperature changes, achieving 100°C variations within milliseconds, significantly outperforming the slower response of precursor flow adjustments, taking tens of seconds. This rapid temperature control is instrumental in creating atomically precise crystal phase quantum dots. We conduct an in-depth study of droplet geometry during these phase transitions, revealing critical insights into the growth dynamics. Furthermore, by applying an external electric field, we successfully deform the catalytic droplet, effectively decoupling the contact angle from the crystal phase formation process. This experimental approach underscores the complex interplay between physical conditions and nanowire growth mechanisms.
In conclusion, using microheaters within a TEM with an integrated gas handling system has enabled a detailed study of the growth dynamics and heterostructure formation in III-V nanowires. By having the advantage of instantaneous temperature changes, we have demonstrated the ability to form crystal phase quantum dots with atomic precision. Furthermore, our findings challenge the traditional coupling of the contact angle as a driving force for the crystal phase formation. This research paves the way for new methodologies in nanowire synthesis, potentially revolutionizing the approach to designing materials for quantum and nanotechnological applications.

Graphic:



Keywords:

MEMS chips, III-V-Nanowires, Contact angle

Reference:

Hastrup et al. Sci. Rep. 10, 14911 (2020)
N. Akopian et al. Nano Lett. 10, 1198–1201 (2010)
F. Panciera et al., Nature Comm. 7, 12271 (2016)
K. Molhave et al. Small 4, 1741 (2008)
M. Tornberg et al. Microscopy and Microanalysis 20, 1484-1492 (2022)