10 ANNIVERSARY

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Growth of few-layer van der Waals materials on semiconductor nanowires

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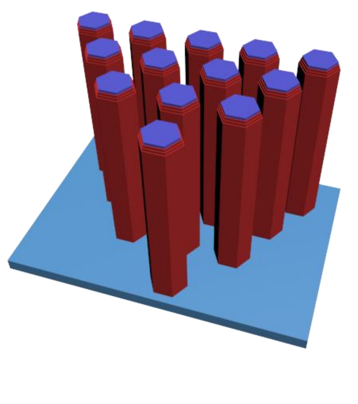
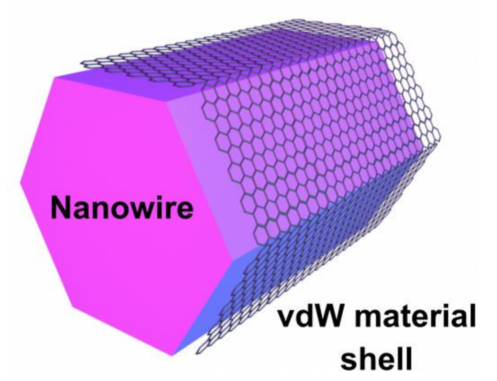
Introduction



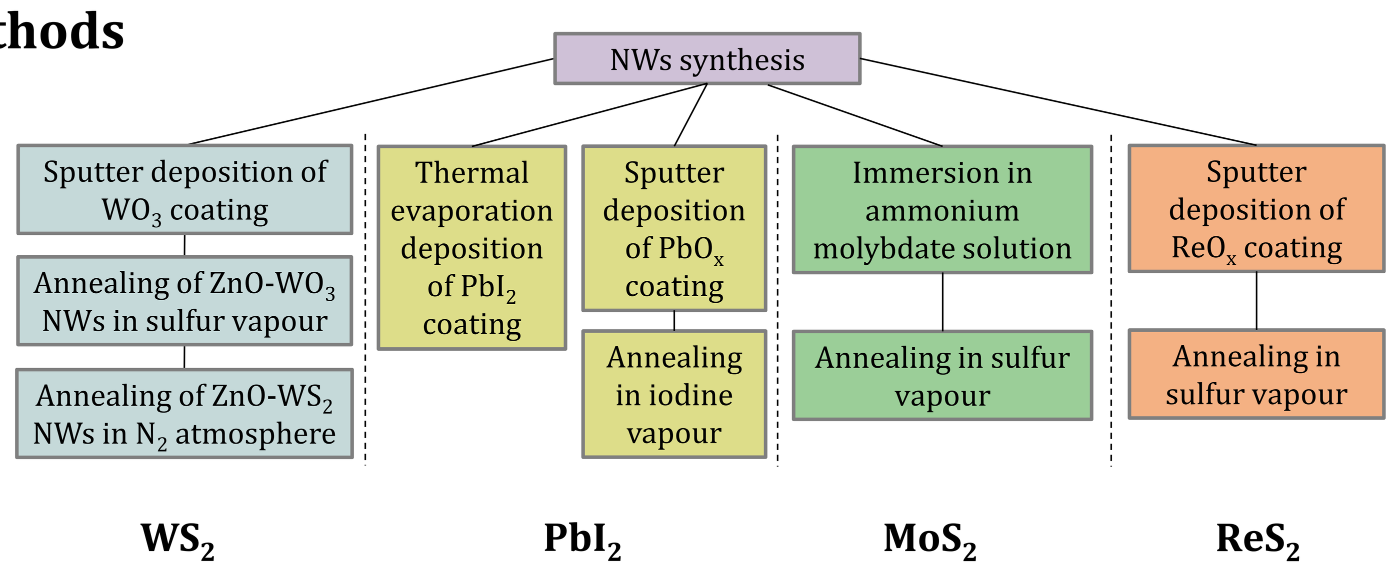
Nanowires (NWs) – 1D nanostructures – are being explored as promising materials for various applications [1]. One of the research directions is combining different materials in hybrid NW-based nanostructures to obtain new functionalities and study fundamental phenomena at nanoscale.

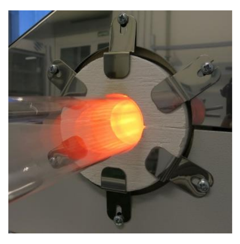
Layered 2D van der Waals (vdW) materials have attracted great interest during the last decade due to the vast amount of potential novel applications for these materials and emerging physical phenomena in 2D systems. There is an on-going search for large-scale synthesis methods of 2D vdW materials on different substrates before any practical applications can be realized [2].

Combining NWs and vdW materials in *core-shell* heterostructures could lead to new knowledge about the interface formation between different materials and solid-state reactions in such systems, to novel nanostructures with enhanced properties, and development of new vdW materials synthesis methods as NWs are a convenient template to study materials growth. Here, we report growth of various vdW materials on different semiconductor NWs using a general two-step approach.



Synthesis methods





Characterization methods

- Scanning electron microscopy (SEM)
- Transmission electron microscopy (TEM) + Selected area electron diffraction (SAED)
- X-ray powder diffraction (XRD)
- Micro-Raman spectroscopy
- Photoluminescence measurements
- Two-terminal single-nanowire device fabriaction for photoelectric measurements

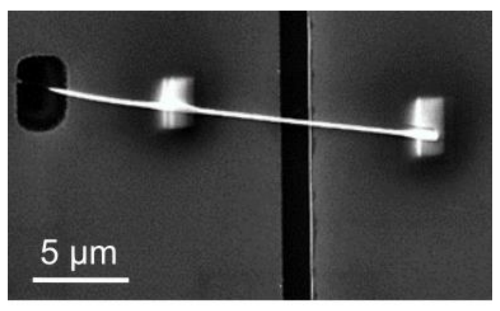


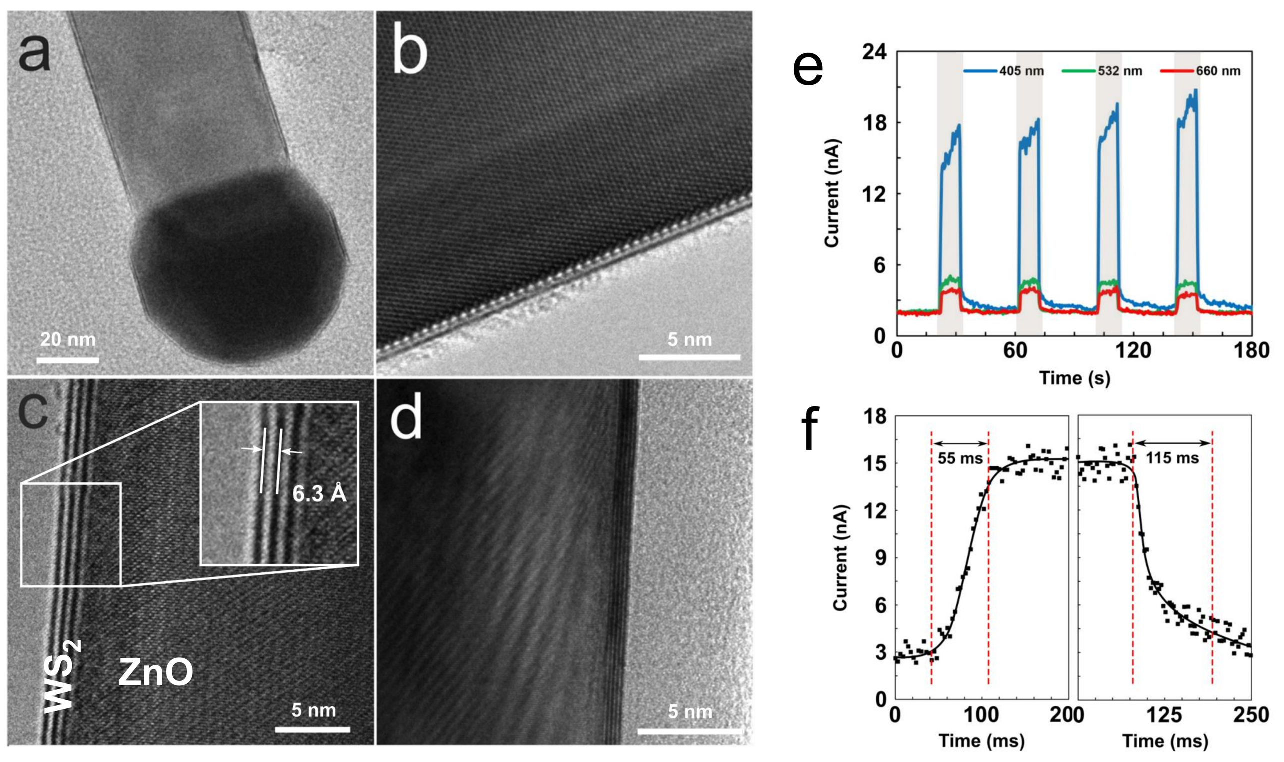
Fig. 1. **A core-shell nanowire on top of gold microelectrodes.**

ZnO-WS_2 NWs

E. Butanovs et al. Fast-response single-nanowire photodetector based on ZnO/WS2 core/shell heterostructures. *ACS Appl. Mater. Interfaces.* 10, 13869-13876 (2018)

B. Polyakov et al. Unexpected epitaxial growth of a few WS2 layers on {11¯00} facets of ZnO nanowires. *J. Phys. Chem. C.* 120, 21451-21459 (2016)

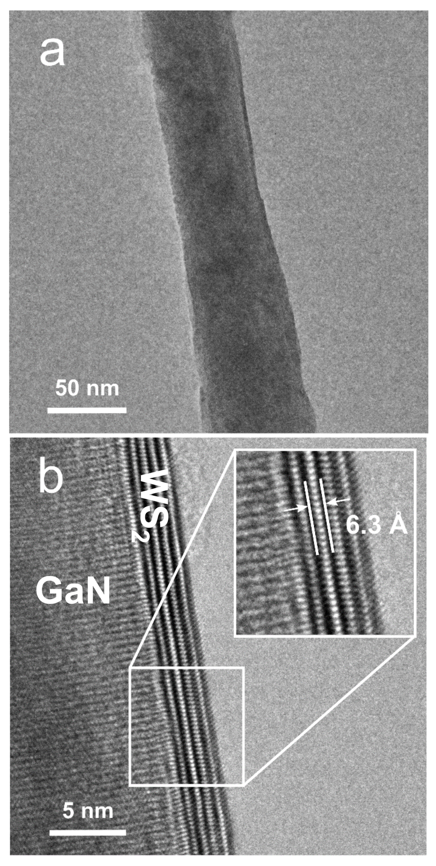
Fig. 2. **TEM images of ZnO-WS_2 core–shell NWs at small (a) and high magnifications (b–d). On–off photoresponse of ZnO-WS_2 single NW photodetector (e); corresponding time-resolved photoresponse measurement (f) (at 1 V bias and 1 W/cm² light intensity).**



See more in Boris Polyakov poster: Fast-Response Single-Nanowire Photodetector Based on ZnO-WS_2 Core-Shell Nanowire Heterostructures!

GaN-WS_2 NWs

Fig. 3. **TEM images of GaN-WS_2 core–shell NWs at small (a) and high magnification (b). The inset shows the measured atomic interlayer distance between WS_2 layers**



GaN-, ZnS- and ZnO-ReS_2 NWs

E. Butanovs et al. Synthesis and characterization of GaN/ReS2, ZnS/ReS2 and ZnO/ReS2 core/shell nanowire heterostructures. *Appl. Surf. Sci.* 536, 147841 (2021)

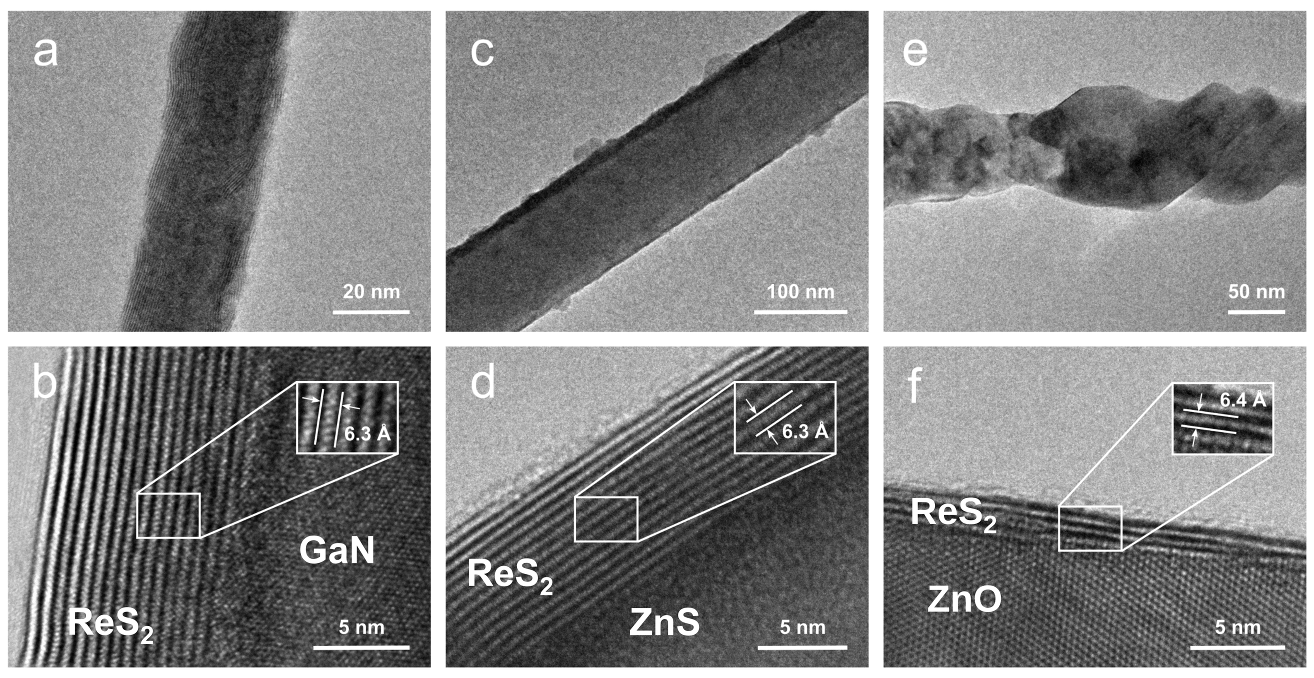


Fig. 4. **TEM images at different magnifications of as-grown (a,b) GaN-ReS_2, (c,d) ZnS-ReS_2, and (e,f) ZnO-ReS_2 core-shell NWs. The insets show the measured atomic interlayer distances between ReS_2 layers.**

ZnO-MoS_2 NWs

E. Butanovs et al. Synthesis and characterization of ZnO/ZnS/MoS2 core-shell nanowires. J. Crys. Growth. 459, 100-104 (2017)

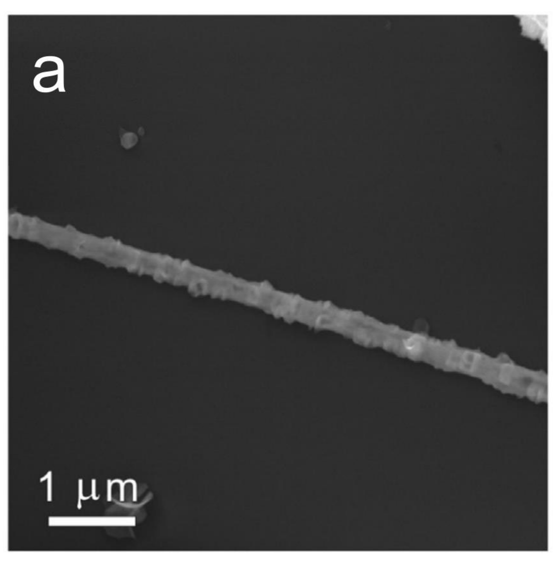
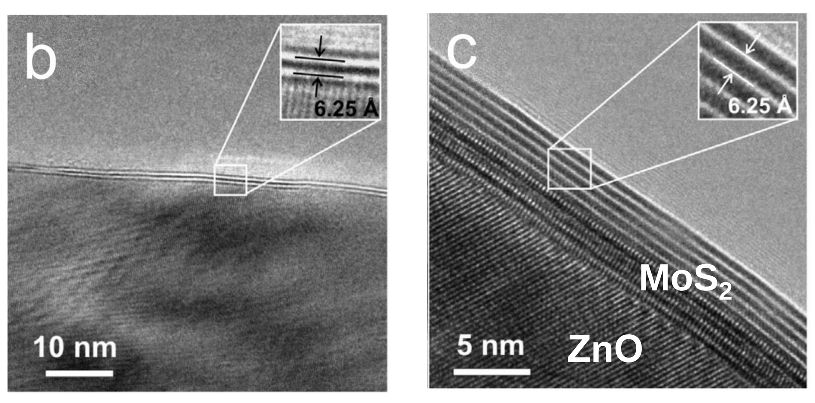


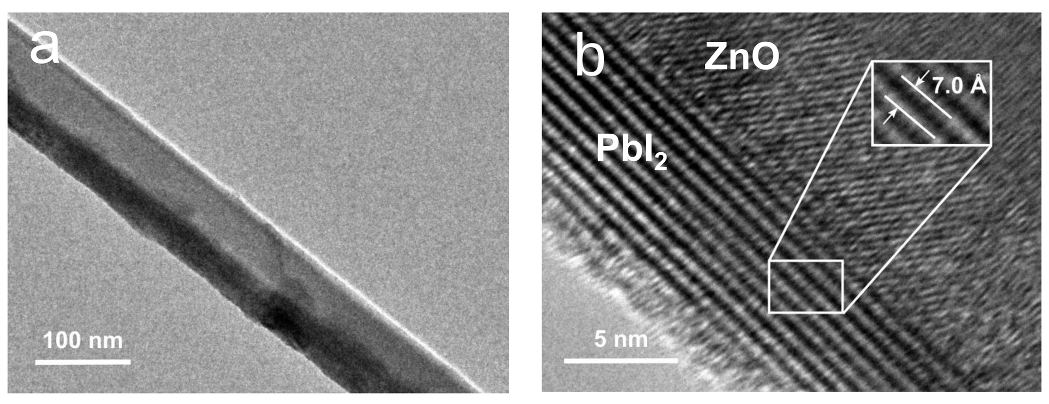
Fig. 5. **SEM image (a) and TEM images (b, c) of ZnO-MoS_2 core shell NWs**

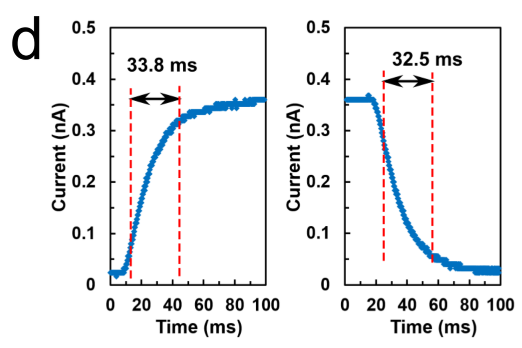


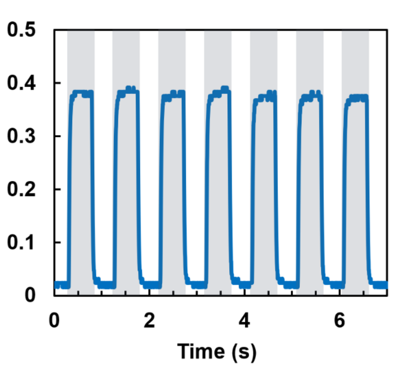
ZnO-PbI_2 NWs

E. Butanovs, S. Piskunov, A. Zolotarjovs, B. Polyakov. Growth and characterization of PbI2-decorated ZnO nanowires for photodetection applications. *J. Alloys Compd.* 825, 154095 (2020)

Fig. 6. **TEM images of PbI_2-decorated ZnO NWs at small (a) and high magnifications (b); on–off photoresponse measurement of ZnO-PbI_2 single NW photodetector (c); corresponding time-resolved photoresponse measurement (d) (at 1 V bias and 1 W/cm² light intensity of 405 nm wavelength)**







Summary and outlook

- We have demostrated growth of ZnO-WS_2, GaN-WS_2, GaN-ReS_2, ZnS-ReS_2, ZnO-ReS_2, ZnO-PbI_2 and ZnO-MoS_2 hybrid 1D nanostructures by a simple two-step method: deposition of a sacrificial shell on the NWs (e.g. WO_3, ReO_x, PbO_x) and its subsequent transformation to a layered material in a reactive vapour (e.g. sulfure, iodine) at high-temperature.
- The synthesis methods developed in this work are not limited to the demonstrated heterostructures but can be applied for other materials, if their compatibility is considered:
  - the transformation of the sacrificial shell material must occur at a lower temperature than the temperature at which NW core reacts with the vapour and recrystallizes;
  - to grow the layered material uniformly around the NW, usually the symmetry and the material lattice parameters should be similar, otherwise the layered material grows out-of-plane or as islands.
- With finely tuned process parameters, such as pre-deposited oxide thickness, temperature, sulfur vapour and carrier gas flow, precise control over the number of layers should be achievable with this method.

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[2] Duong, D. L., Yun, S. J. & Lee, Y. H. van der Waals Layered Materials: Opportunities and Challenges. ACS Nano 11, 11803–11830 (2017)

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