Omer Arif

- **Thesis Advisor: Prof. Lucia Sorba**
- **PhD in Nanoscience**

III year

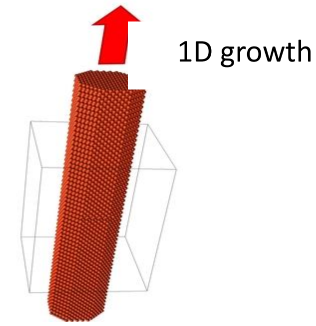
- **Scuola Normale Superiore, Pisa.**

National Enterprise for nanoScience and nanoTechnology

Semiconductor nanowires (NWs)

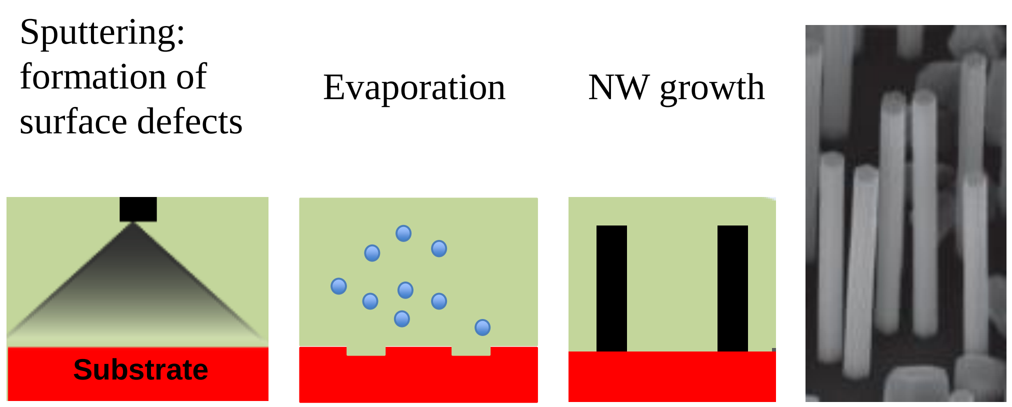
one dimensional crystals

➢ Novel properties:
- high surface/volume ratio
- carriers confinement
- defect-free growth of hetero-structures
- free standing nature

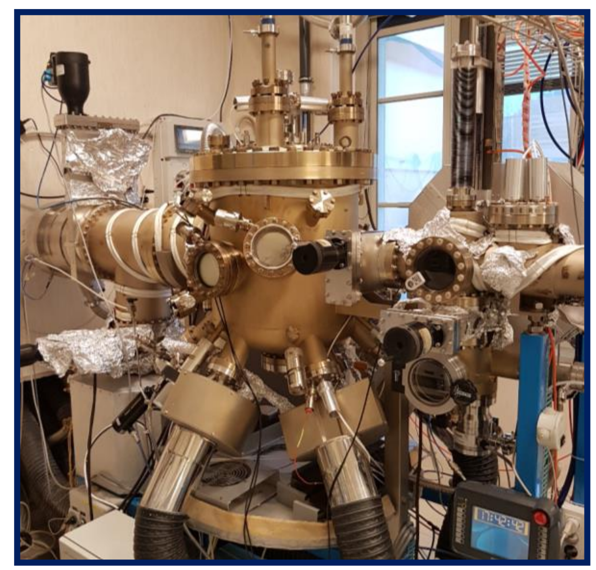


➢ Technological relevance: applications in electronics, photonics, chemical sensing.

Catalyst-free growth:
Vapor-solid mechanism



Chemical Beam Epitaxy



PhD Activities

- Growth and Strain Relaxation Mechanisms of InAs/InP/GaSb Core-Multishell Nanowires

- Transport Measurements of InAs/InP/GaSb CMS NWs

- Growth mechanisms of Self-Assisted InAs/InSb Axial Heterostructured Nanowires

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Growth and Strain Relaxation Mechanisms of InAs/InP/GaSb Core-Multishell Nanowires

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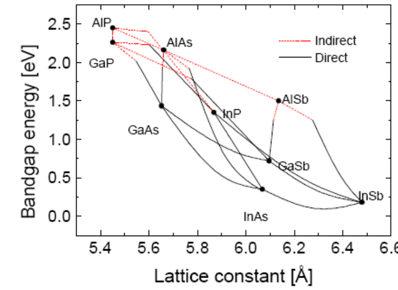
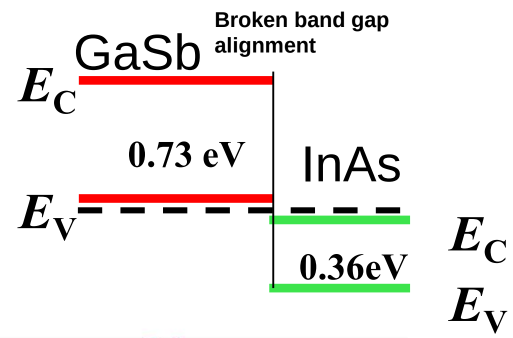
Motivations

InAs/GaSb Heterointerface:

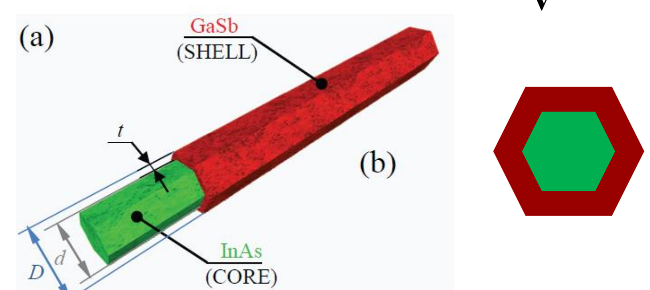
- very low lattice mismatch → low-strain radial (coaxial) growth
- broken-gap band alignment → Tunnel field effect transistors, Esaki diodes, ambipolar devices, topological states.





Core-shell (CS) geometry:

- coexistence of mobile electrons and holes in facing regions of the sample
- Radial junctions are suitable for the realization of ambipolar devices.

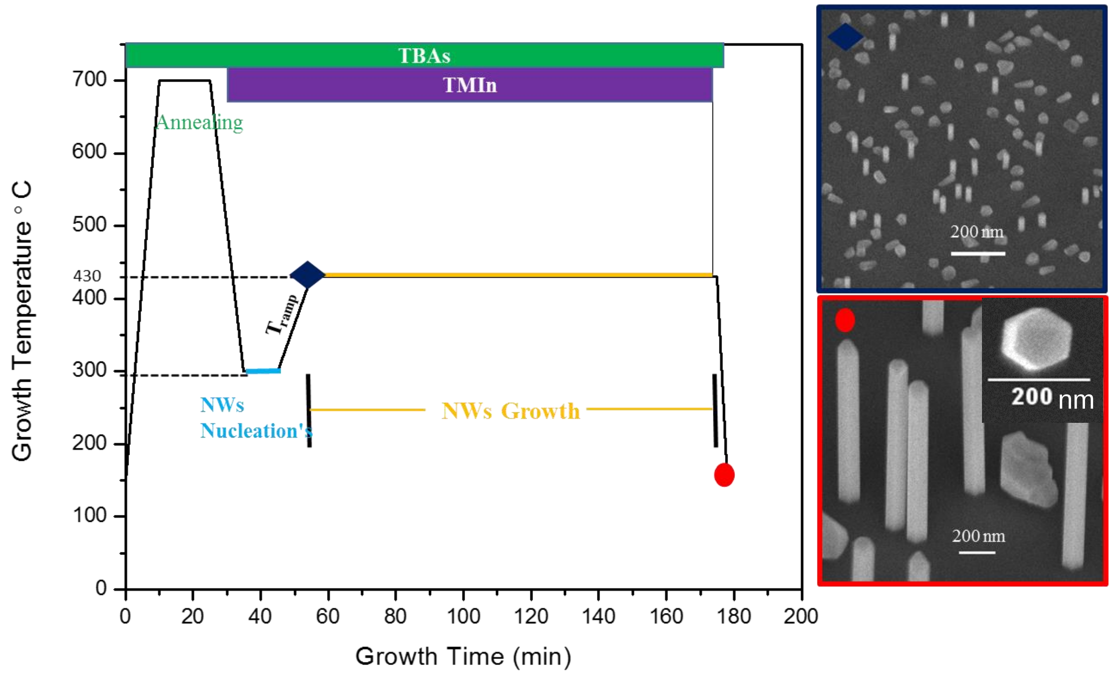


Why Choose an InP barrier between InAs and GaSb?

- To have two conductive channels separated by an insulating layer (p-i-n device configuration) and to enhance the tunneling current.
- InP introduce strain in the system So it is worth to understand relaxation mechanisms in this system in order to fabricate high quality devices.

Growth optimization of CMS NWs

InAs Core

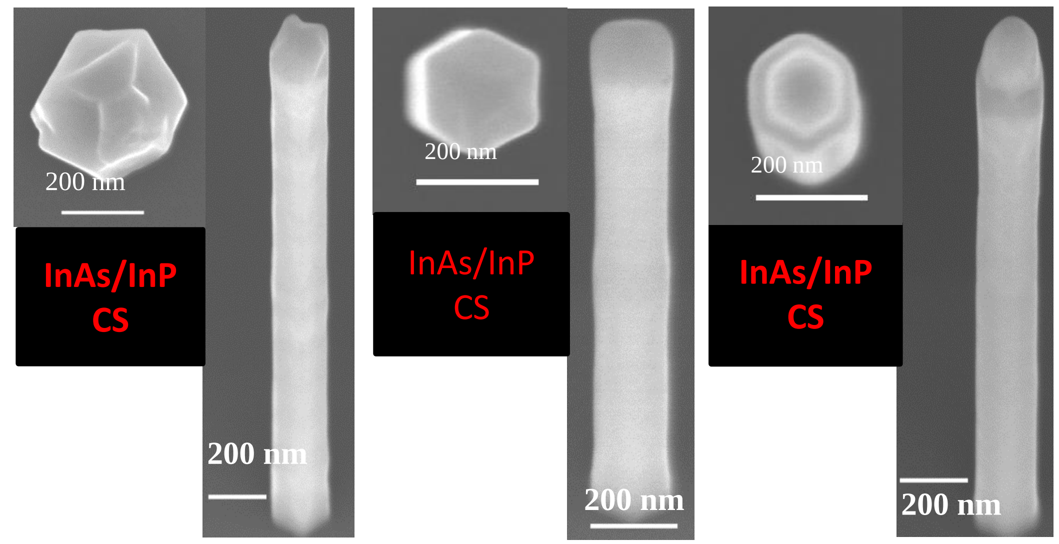


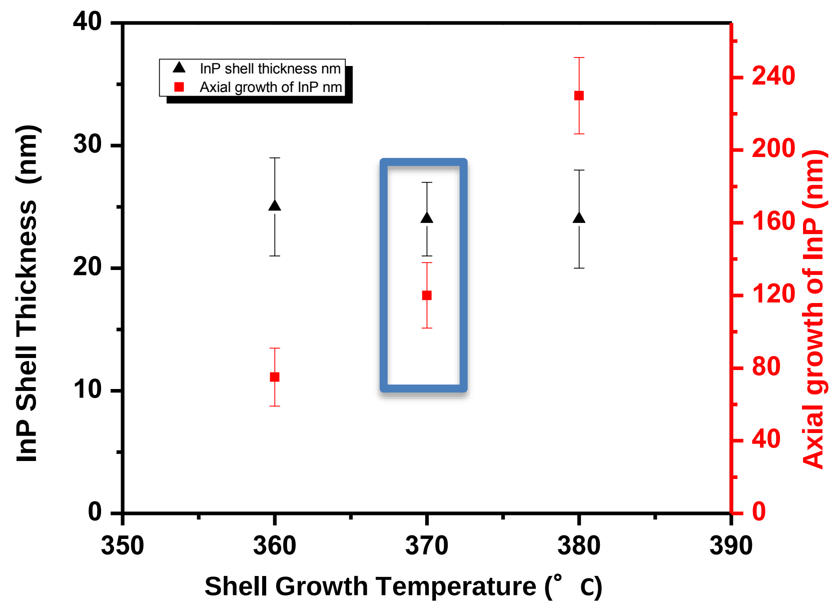
InAs/InP CS NWs

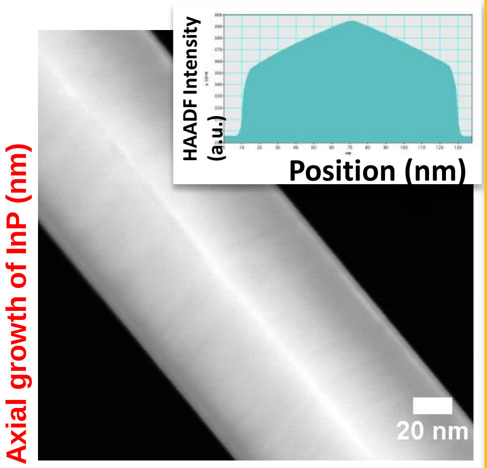
$T_{shell\ growth}$ = 360 ° C

$T_{shell\ growth}$ = 370 ° C

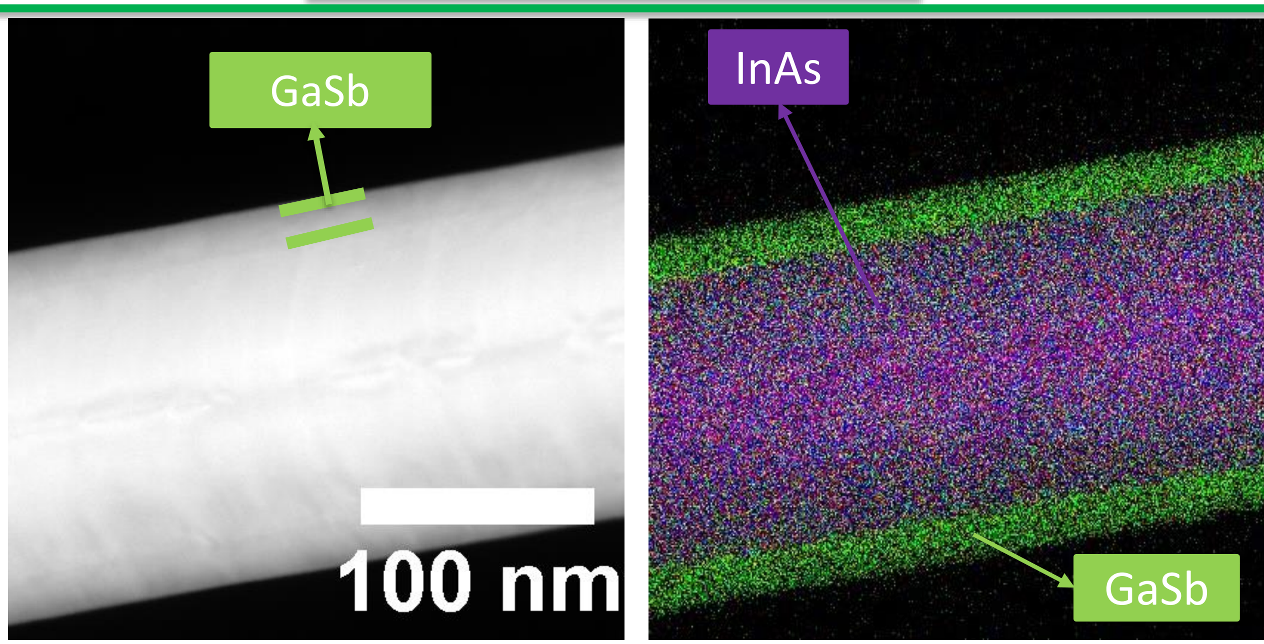
$T_{shell\ growth}$ = 380 ° C







InAs/GaSb CS NWs



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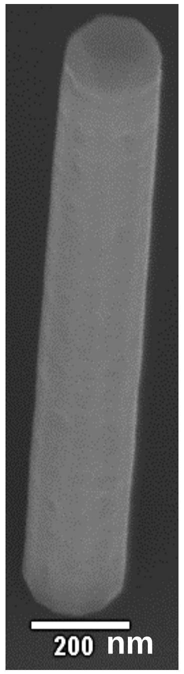
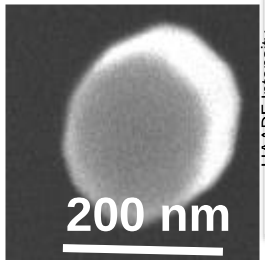
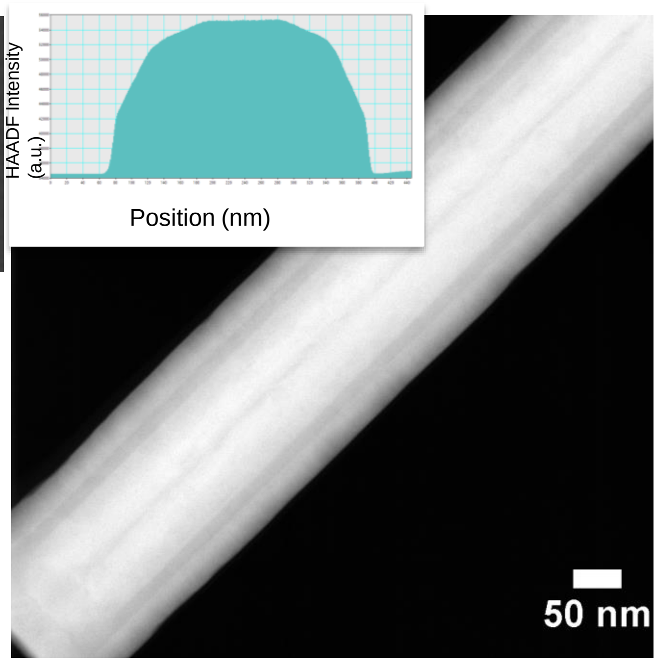
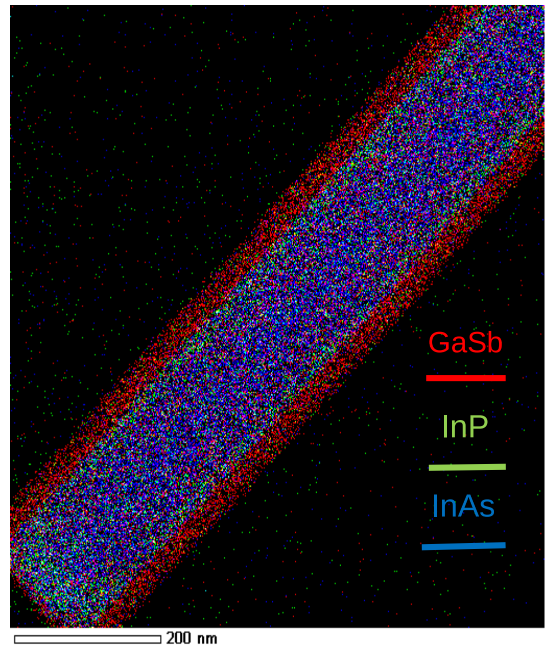
InAs/InP/GaSb CMS NWs

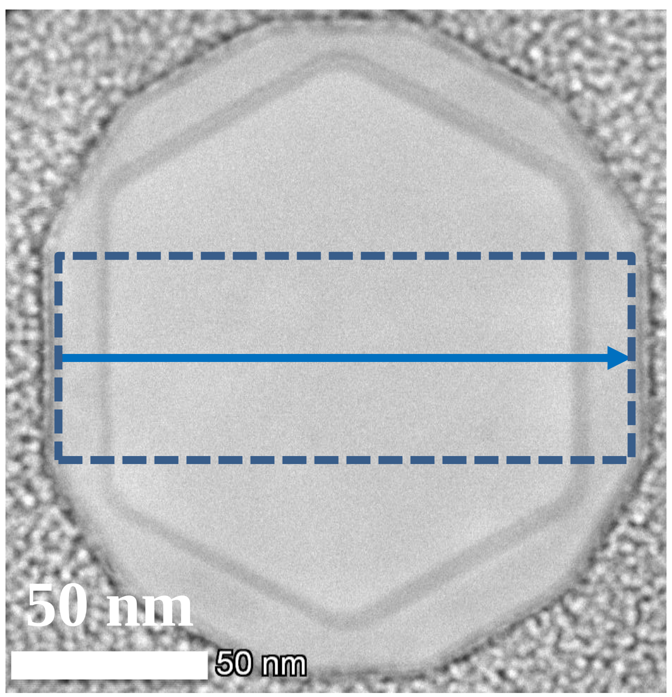


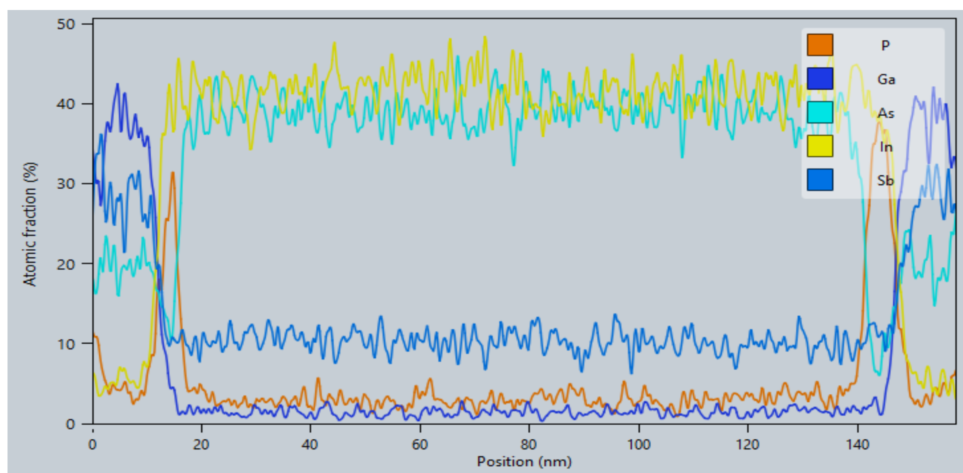






- After optimization of InP and GaSb shell, we combined them in single InAs/InP/GaSb CMS heterostructures NWs.
- The EDS maps confirm the presence of uniformly thick InP and GaSb shell around the InAs core.
- The HAADF intensity profile of InAs/InP/GaSb CMS has twelve side facets.





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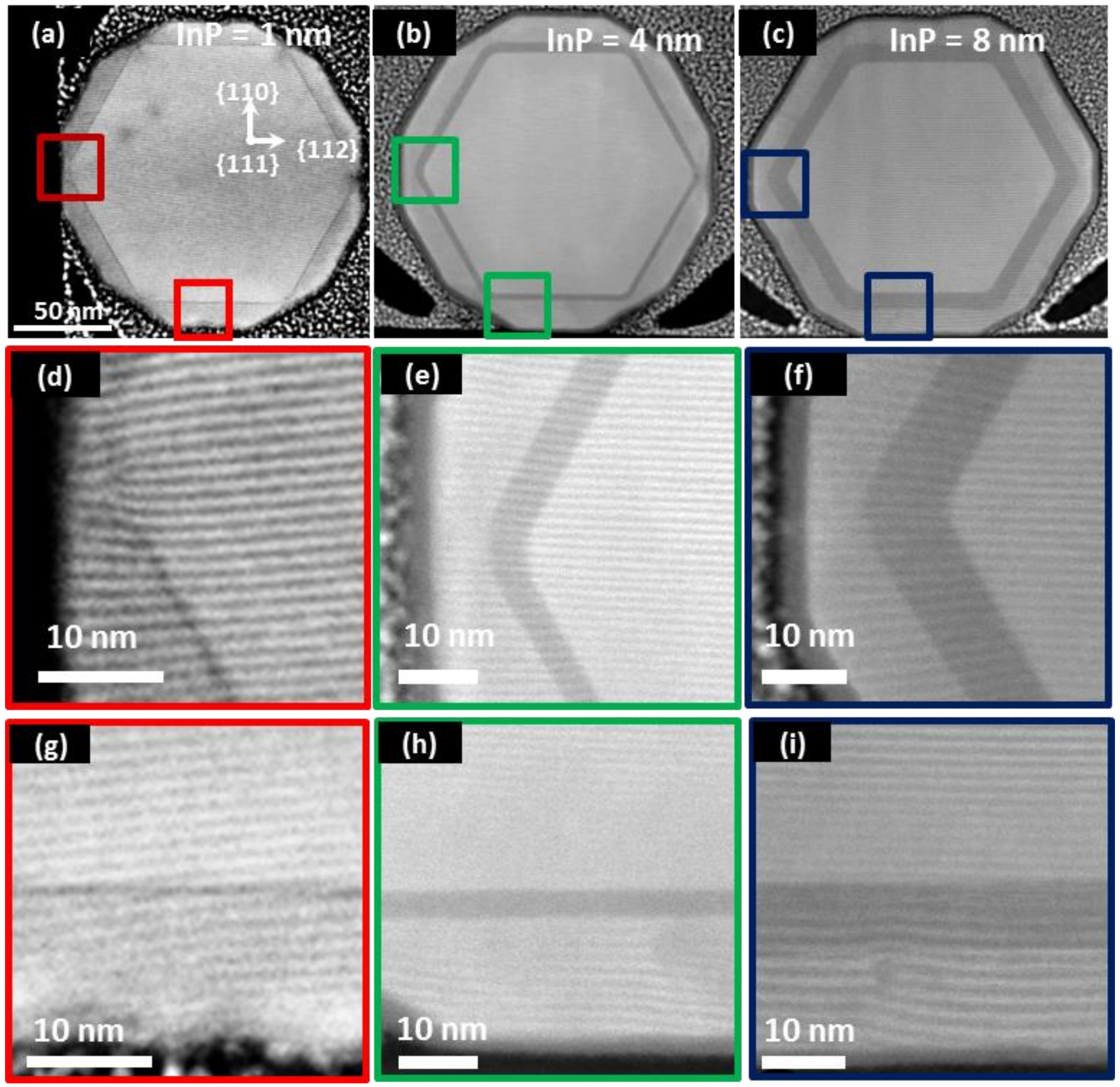
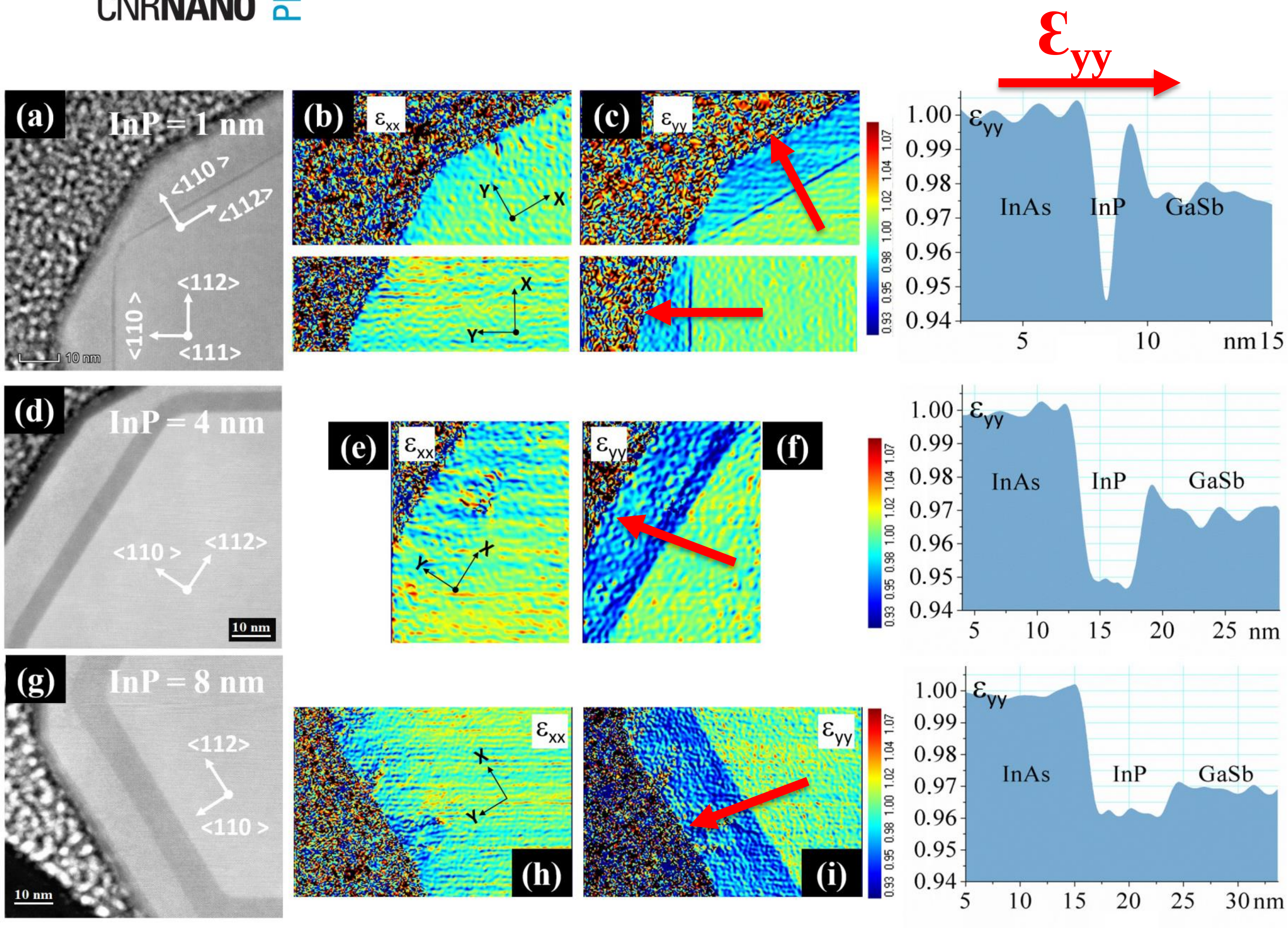
STEM-Moiré Patterns



- Three different samples with 1, 4 and 8 nm nominal thickness of InP barrier were analyzed. Cross-sections lamella of NWs prepared by focus ion beam (FIB).
- GaSb shell growth is higher in the <110> directions as compared to <112> directions.
- Sample with **1 nm thick InP shell**, facets are not well developed at the corner and we found dislocations at the InAs corners.
- Samples with **4 nm thick InP shell**, dislocations are not found at the corners neither at the flat facets.
- Sample with **8 nm thick InP shell**, dislocations found and interfaces between InP and others materials is not flat any more and many steps are observed.

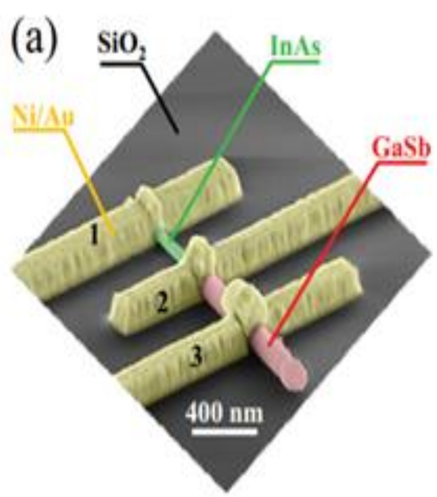
Geometric Phase Analysis Maps

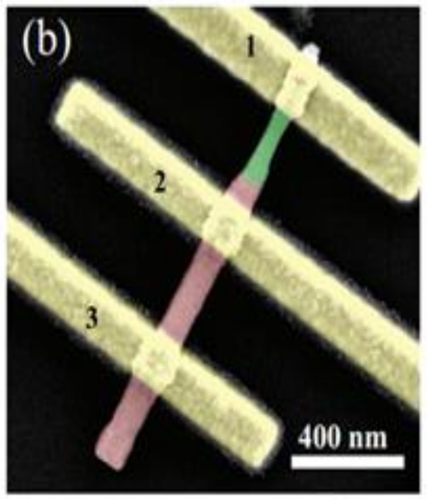


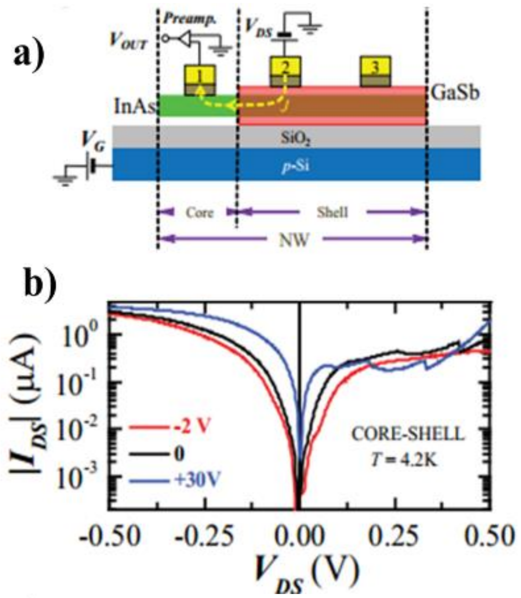
- STEM-HAADF images with the combination of geometric phase analysis maps (GPA).
- For all the samples, the lattice parameters of shells observed parallel to interface is the same of InAs core while perpendicular to interface both InP and GaAsSb have their own lattice parameters.
- For all the samples, the averaged value of ε_{yy} between InAs/InP interface is -5% and between InAs/GaSb -3%.
- Strain analysis suggest that lattice is relaxed through tetragonal distortion.

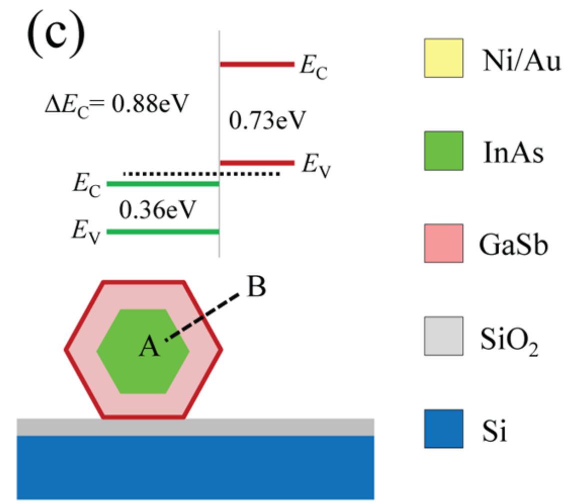
Transport Measurements of InAs/InP/GaSb CMS NWs

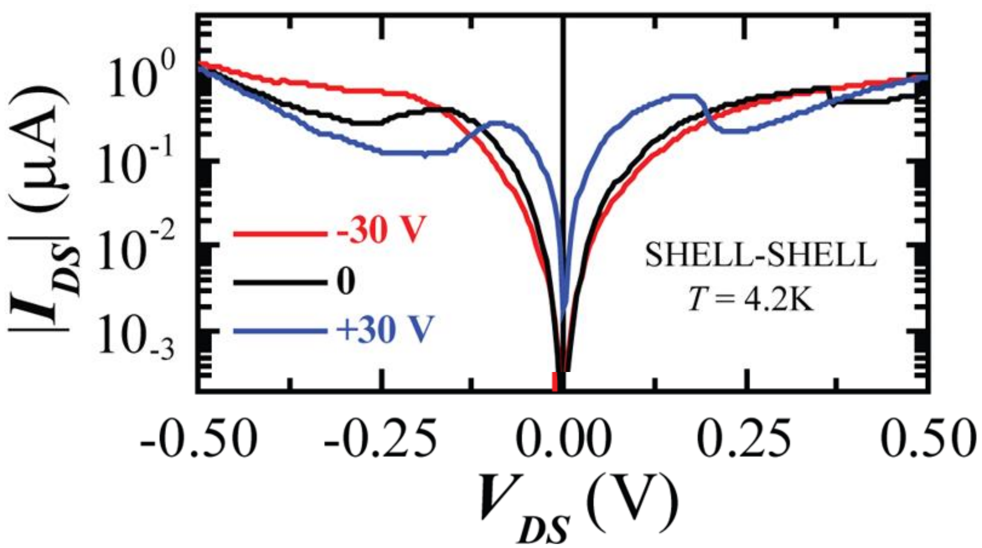
Transport Measurements of InAs/GaSb CS NWs



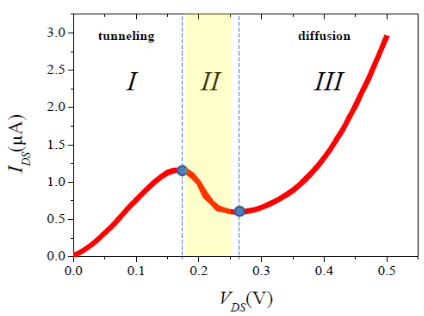


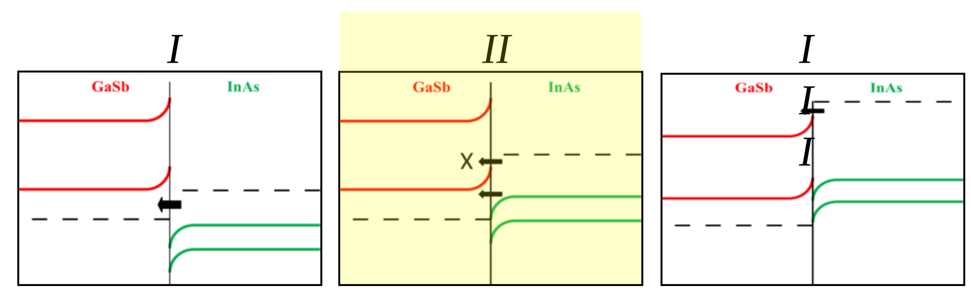






Esaki effect: Negative Differential Resistance (NDR)

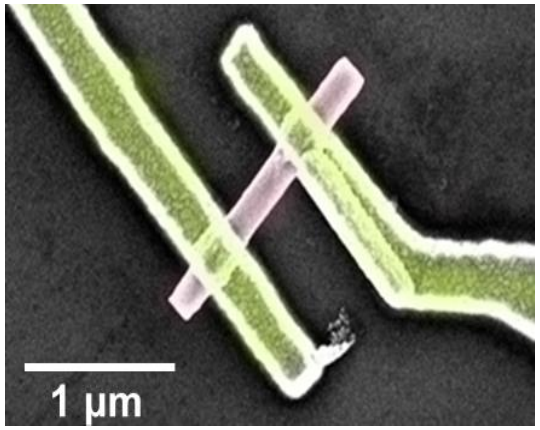


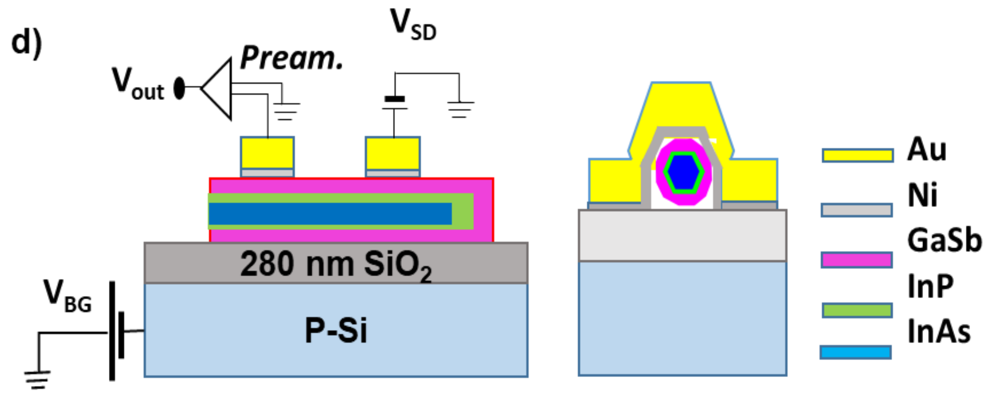


Leo Esaki, Phys. Rev. 109 (2):603 – 604 (1958)

M. Rocci, F. Rossella, U. P. Gomes, V. Zannier, F. Rossi, D. Ercolani, L. Sorba, F. Beltram and S. Roddaro, Nano Letters, 16, 7950–7955 (2016).

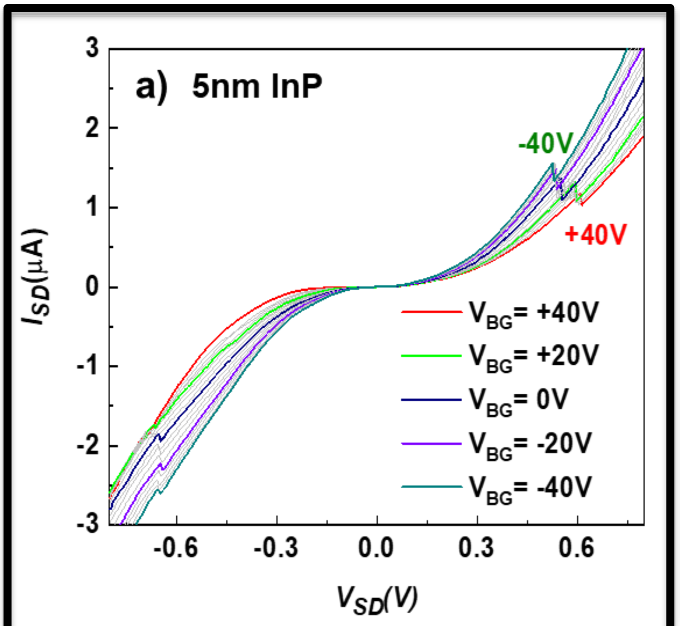
Shell to Shell configuration



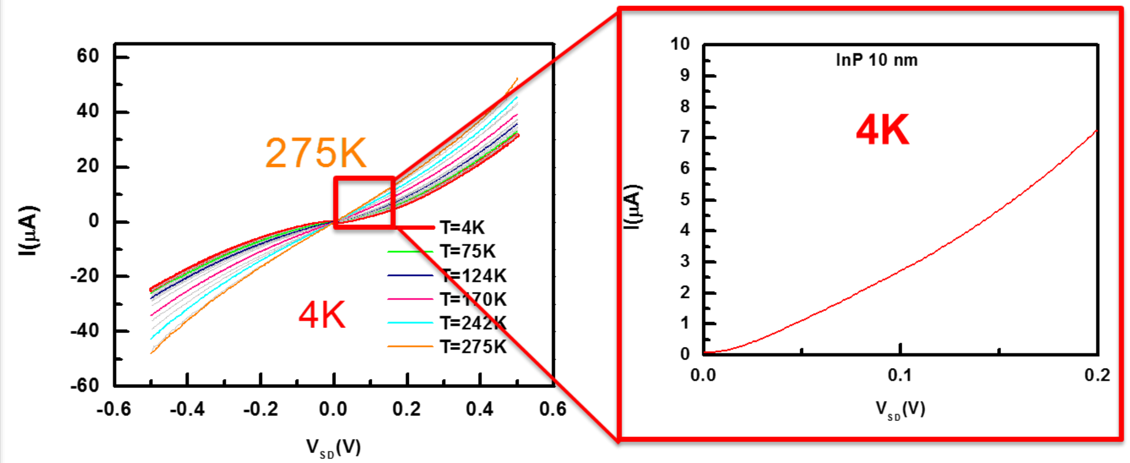


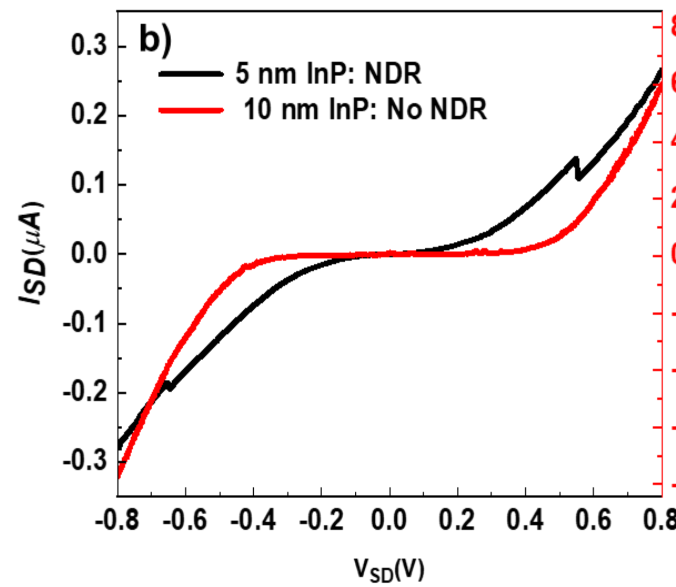
InAs/InP/GaSb CMS NWs with thickness of InP = 5 nm, 10 nm & GaSb = 30 nm

InP = 5 nm



InP = 10 nm





Growth mechanisms of Self-Assisted InAs/InSb Axial Heterostructured Nanowires

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Motivations

InAs/InSb Heterostructured NWs:

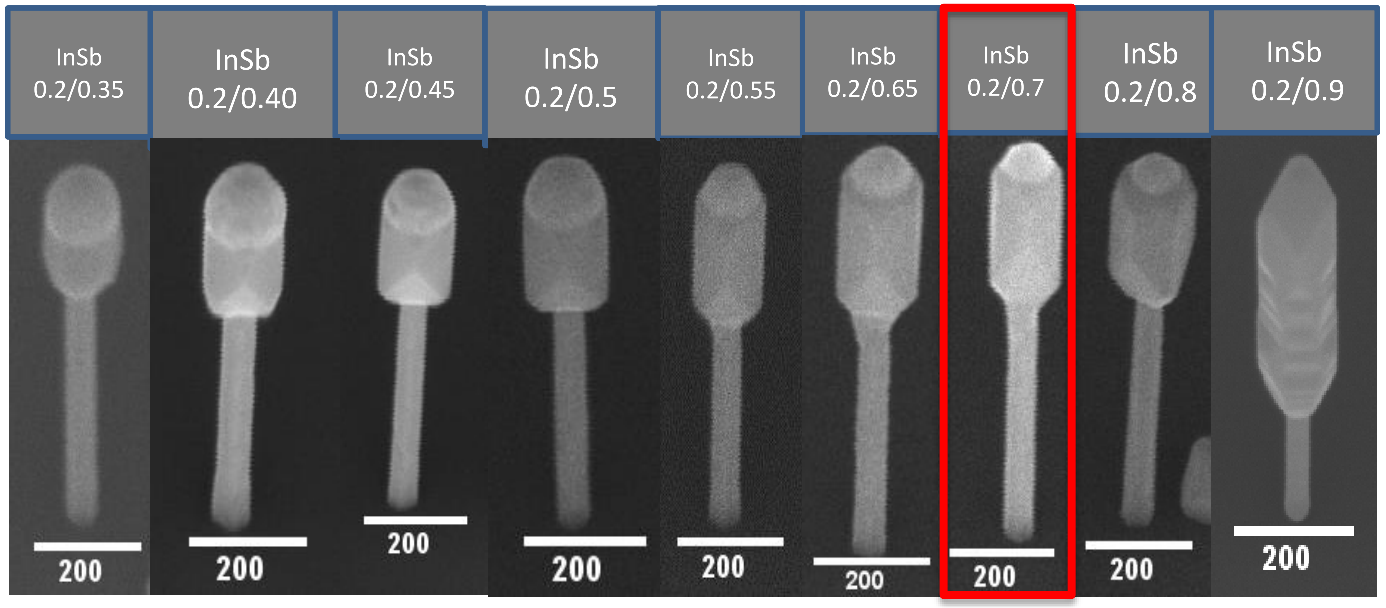
- **Narrow bandgap → infrared optoelectronics.**
- **Extremely high bulk electron mobilities, Small effective masses → high-speed and low-power electronics devices.**
- **Strong spin-orbit interactions → spintronics, topological quantum computing, and detection and manipulation of Majorana fermions.**
- **Growth of nanowires is self assisted without using gold particle which is benificial because gold particle behave as contamination in nanowire which is not suitable for the growth of nanowires on a complementary metal oxide semiconductor platform (CMOS).**

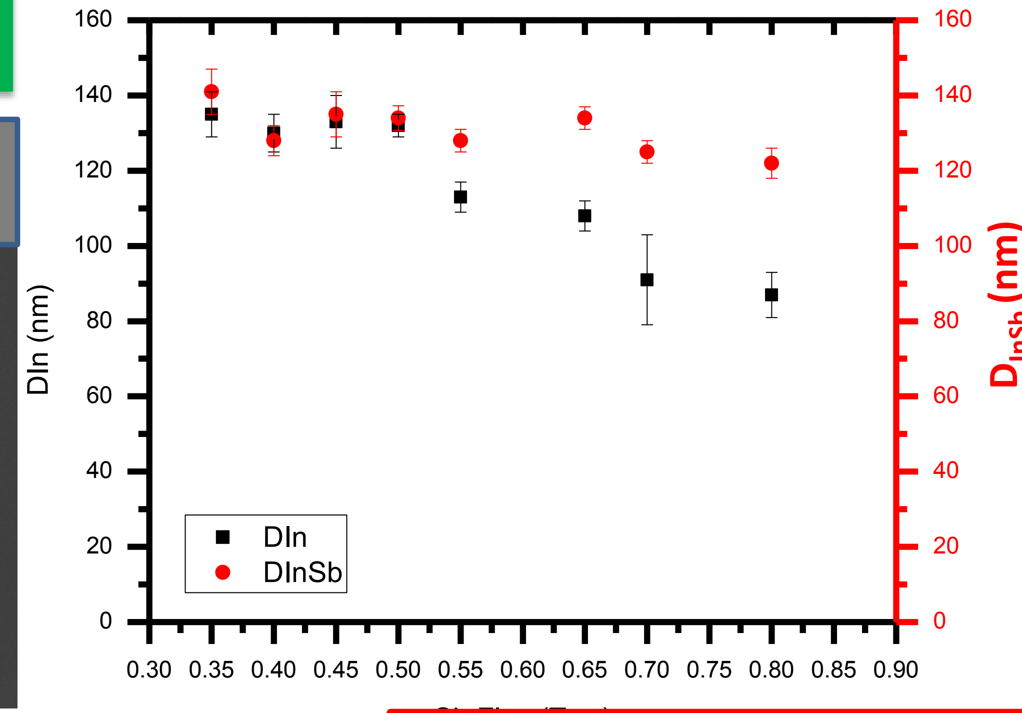
Influence of Sb flux on the InSb segment morphology

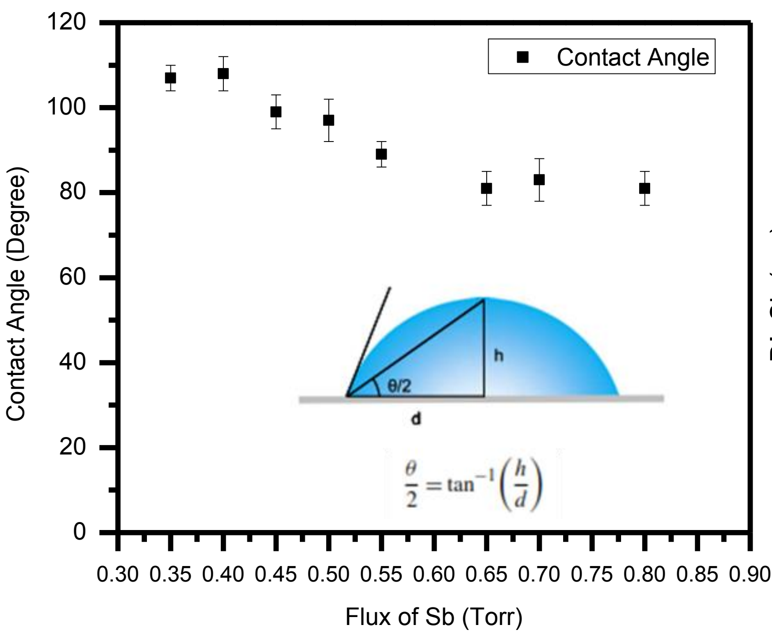
TMIn = 0.2 Torr

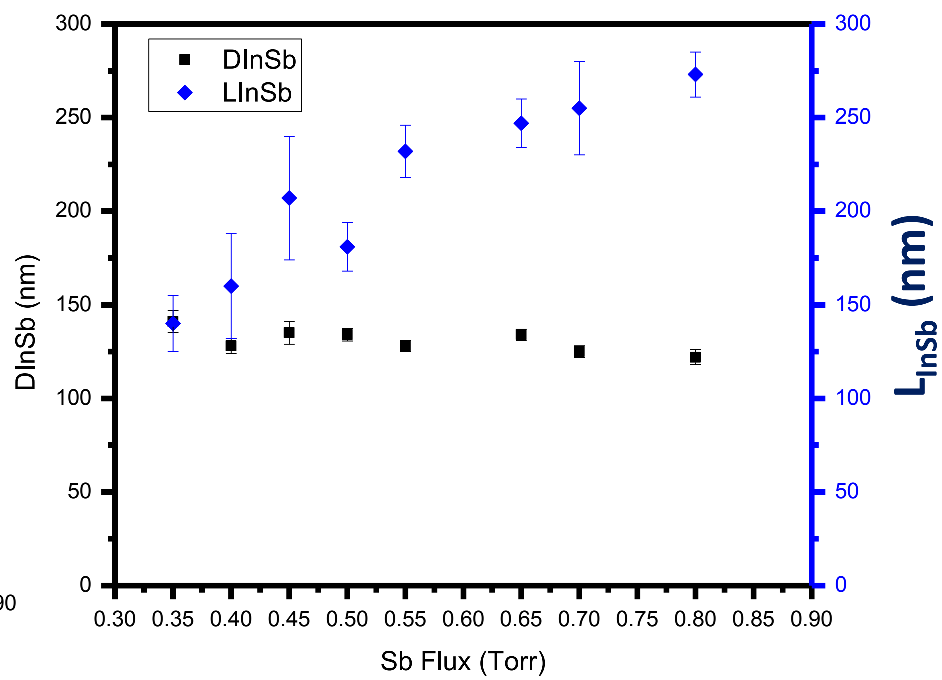
t_{growth} = 60 minutes

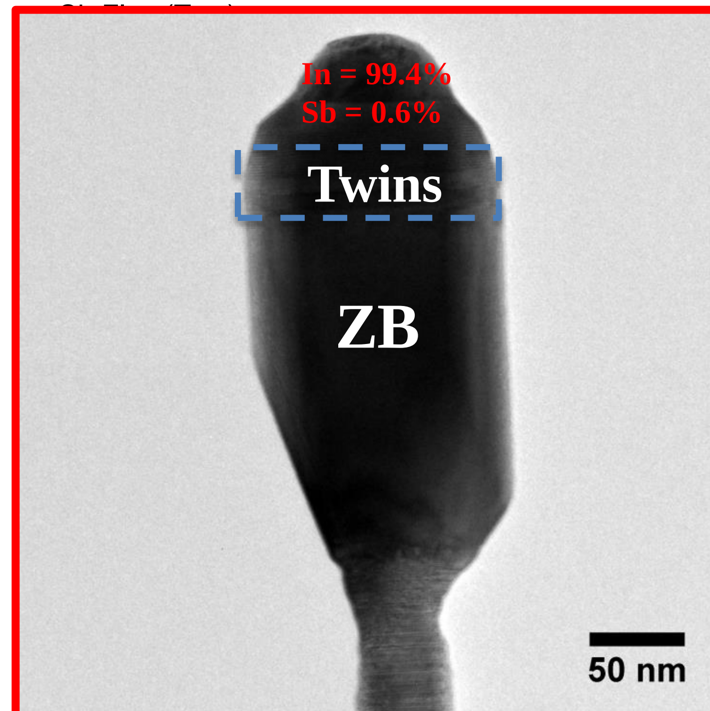
TDMASb = 0.35 to 0.9 Torr









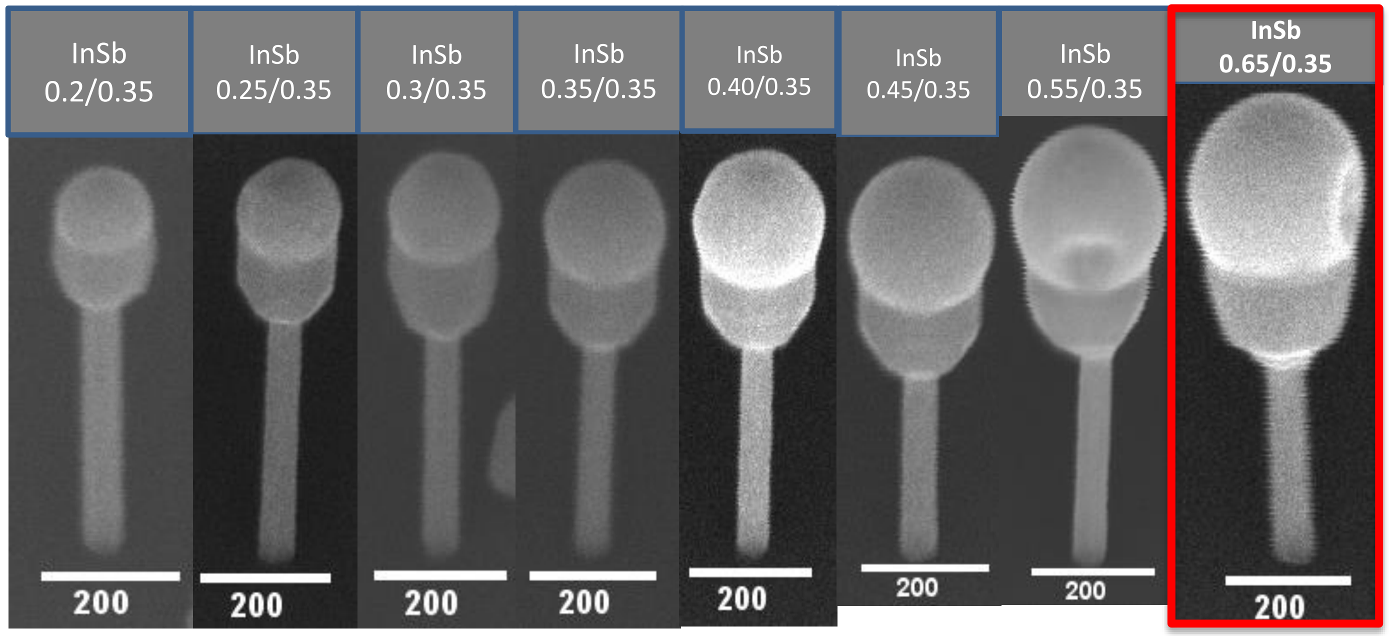


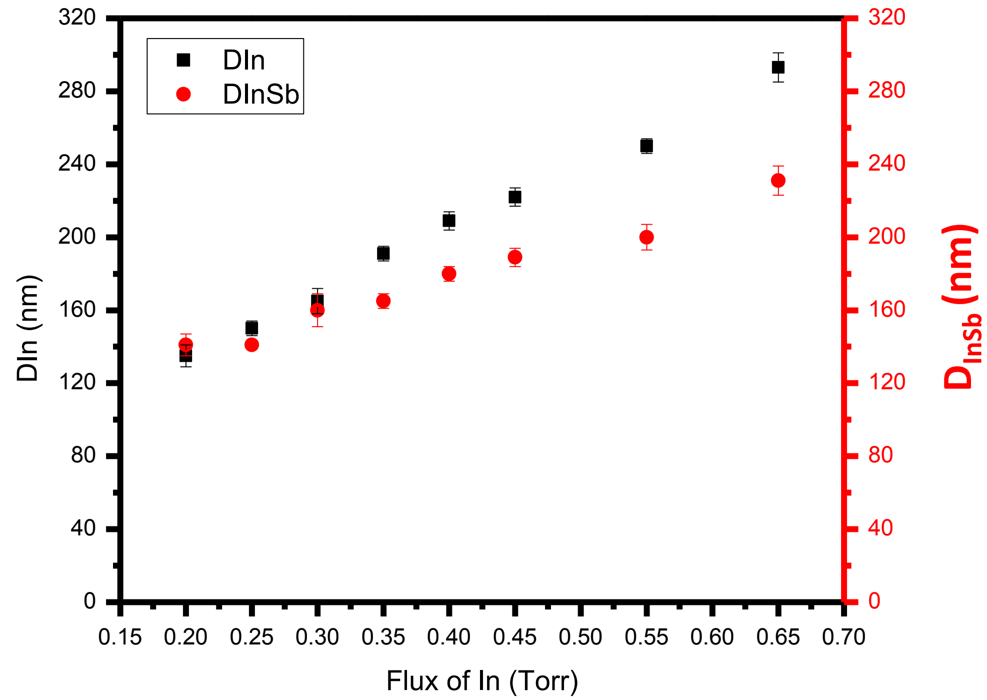
Influence of In flux on the InSb segment morphology

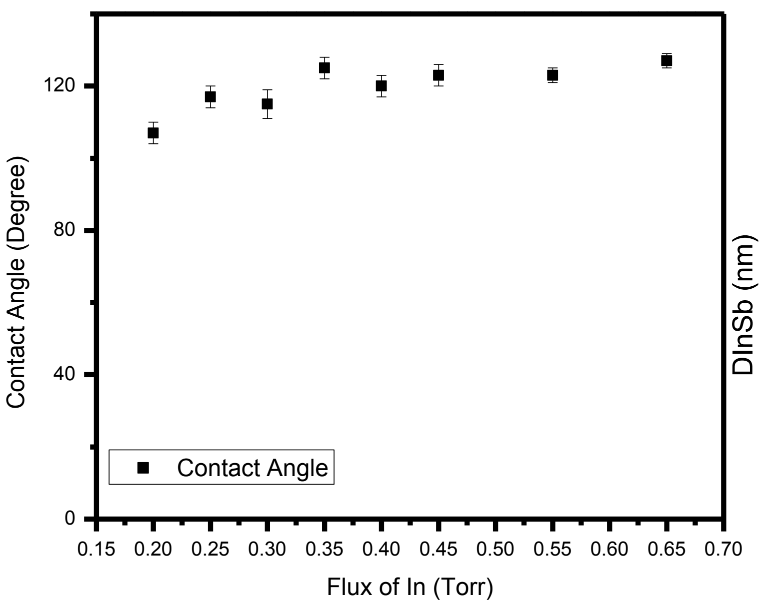
TMIn = 0.2 to 0.65 Torr

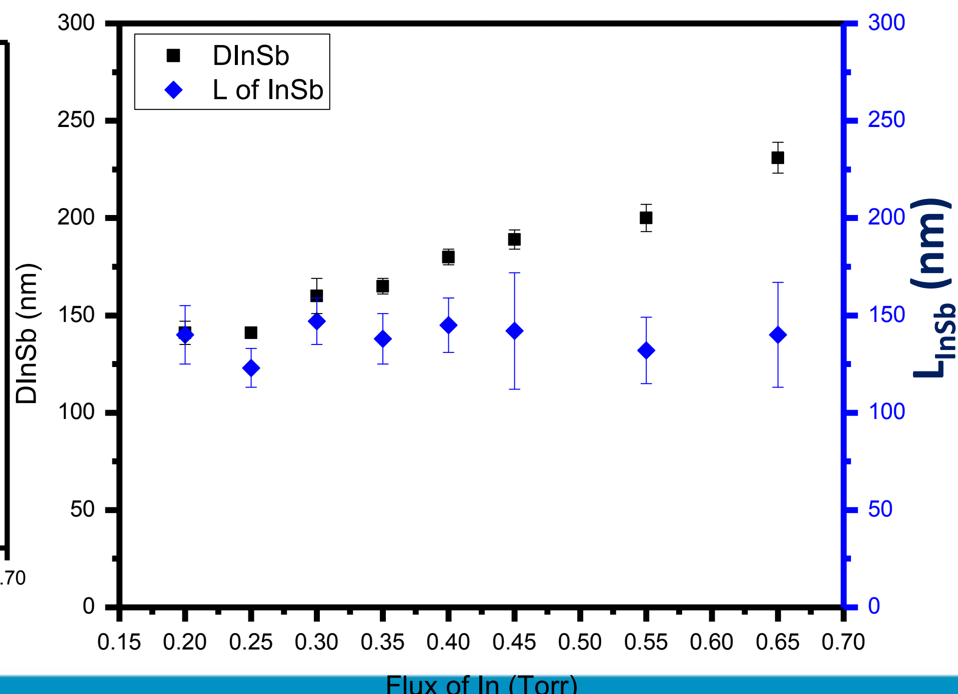
t_{growth} = 60 minutes

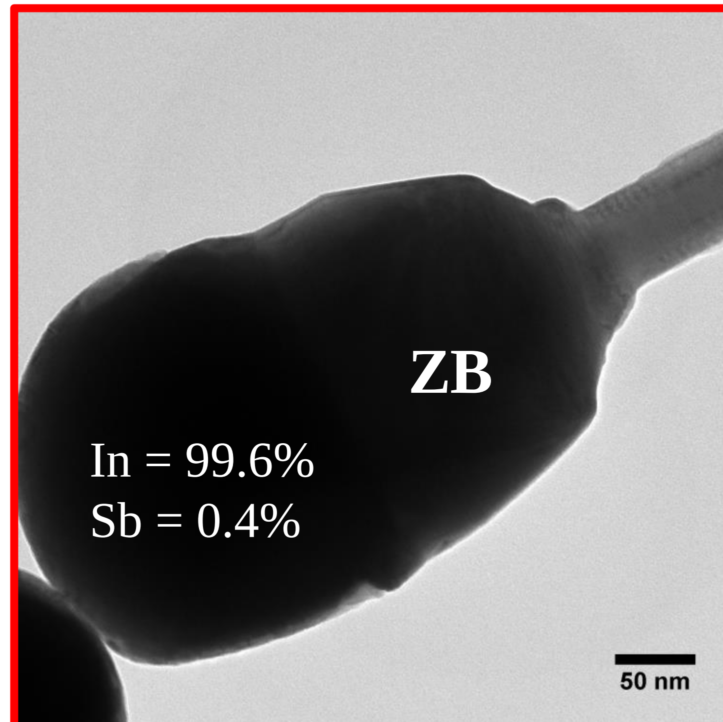
TDMASb = 0.35 Torr







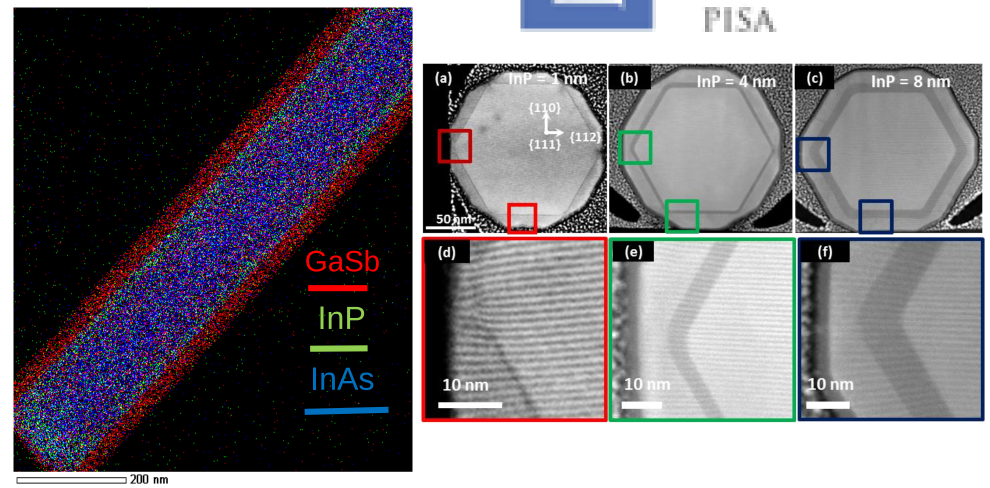




Conclusions

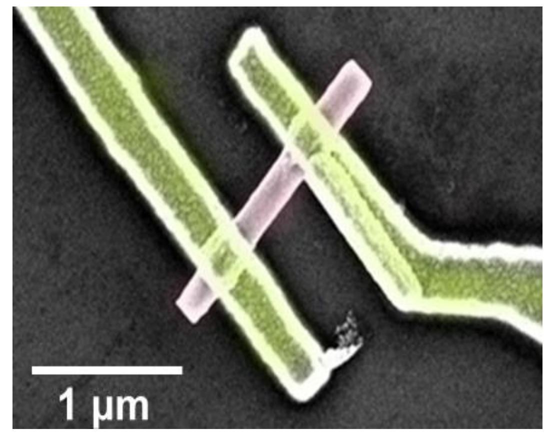
1. **Successfully achieved smooth and homogenous catalyst-free InAs/InP/GaSb CMS NWs. In all the samples InP and GaSb relax strain through tetragonal distortion. For 8 nm thick InP barrier, we have seen some dislocations and steps at the interfaces.**

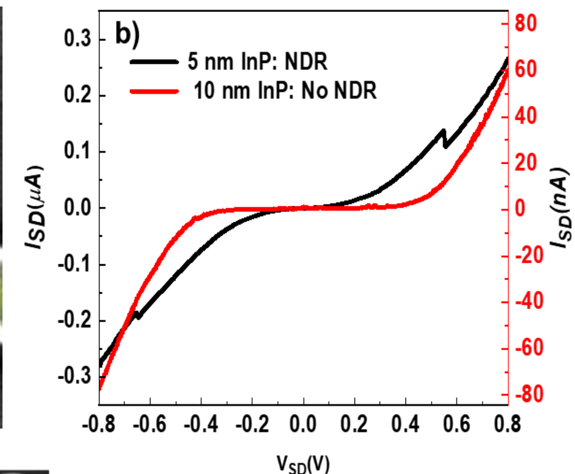
   Note: Manuscript is ready and soon will be submitted to Crystal Growth and Design ACS Journal.



2. **We realized from FET devices that 10 nm thick InP barrier decoupled electrical transport between core and shell.**

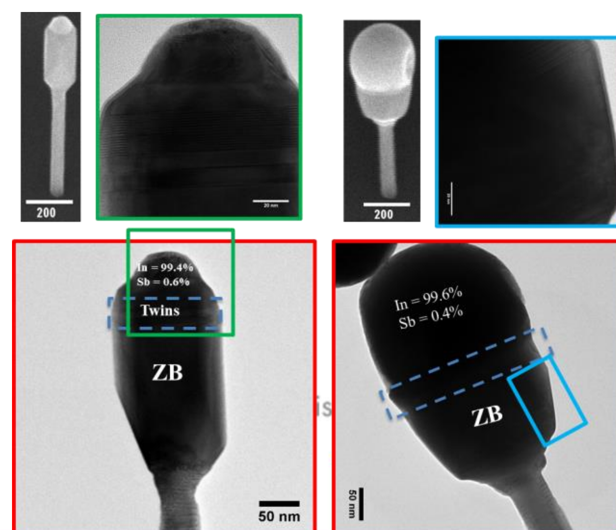
   Note: Manuscript is in preparation and soon will be submitted to Nanoresearch Journal.





3. **Influence of Sb, In flux on the InSb segment morphology:**

- ✓ It is concluded the Sb flux strongly affects the NP shape (R, H and contact angle) and the axial InSb growth rate, whereas it doesn't affect the InSb radial growth.
- ✓ The In flux affects the NP size and contact angle and the InSb diameter, while axial growth rate of InSb is constant.



Future plans

- **The growth mechanisms of InAs/InSb axial heterostructured NWs will be theoretical modelled through the collaboration with Prof. Vladimir Dubrovskii from the University of San Petersburg.**

- **Growth of InAs/InSb Quantum Dots by self assisted growth mode**
- **The limitations with gold assisted method is that gold particle become alloy with group III elements and when it switched from Sb to As it starts etching the nanowires and growth of InAs segment is not possible.**