MBE growth of self-assisted InAs nanowires on graphene

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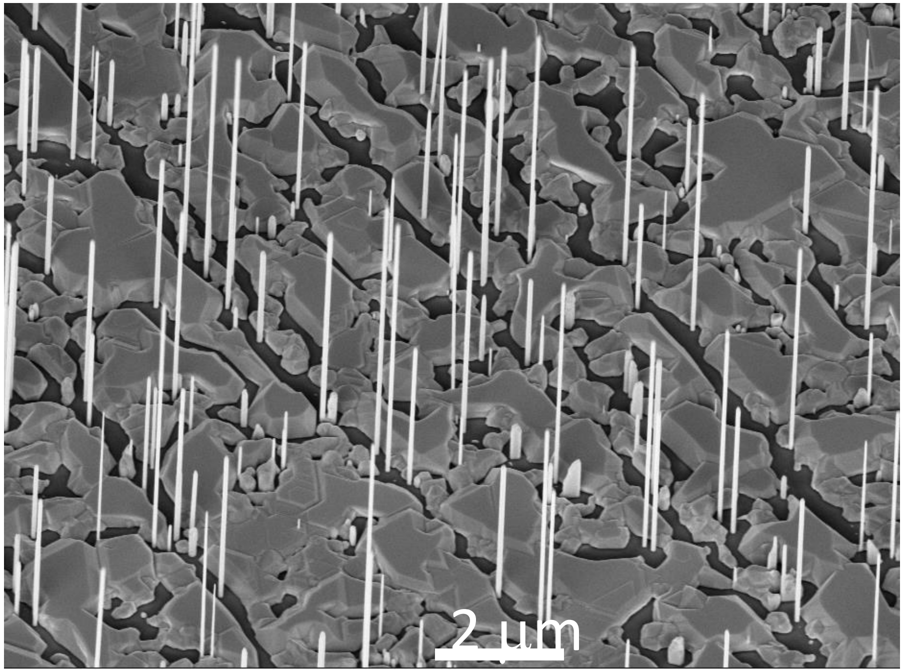


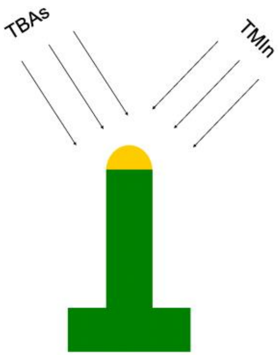
InAs NWs on Graphene

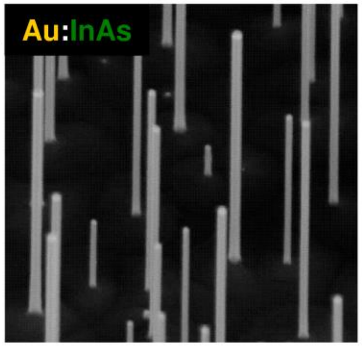
InAs NWs are key role payers in the search for Majorana fermions

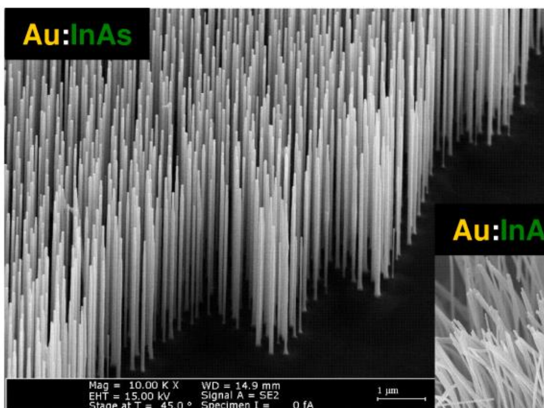
- High aspect ratio
- Excellent (WZ) crystalline quality
- Easy formation of non alloyed contacts
- Fermi level pinned in the conduction band
- Large Lande g-factor
- High spin orbit coupling

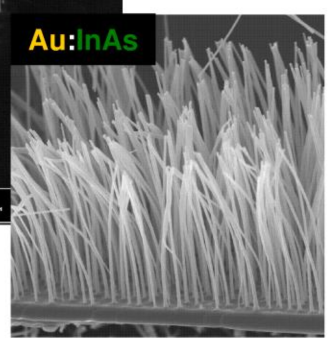
key factors in current mesoscopic physics experiments including the search for *Majorana fermions*

Au-assisted InAs NWs on 111B InAs









Diameter 20-100 nm

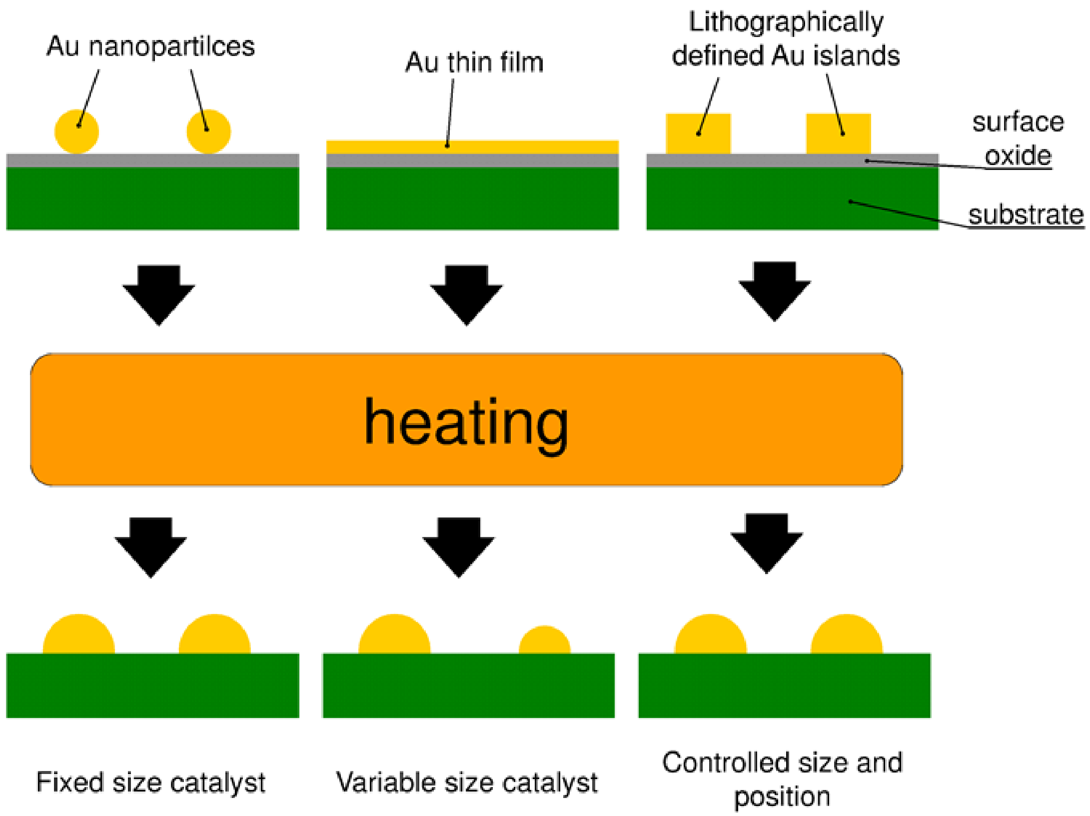
Length up to 2-4 μm

Hexagonal cross section

Perfect wurzite crystal structure

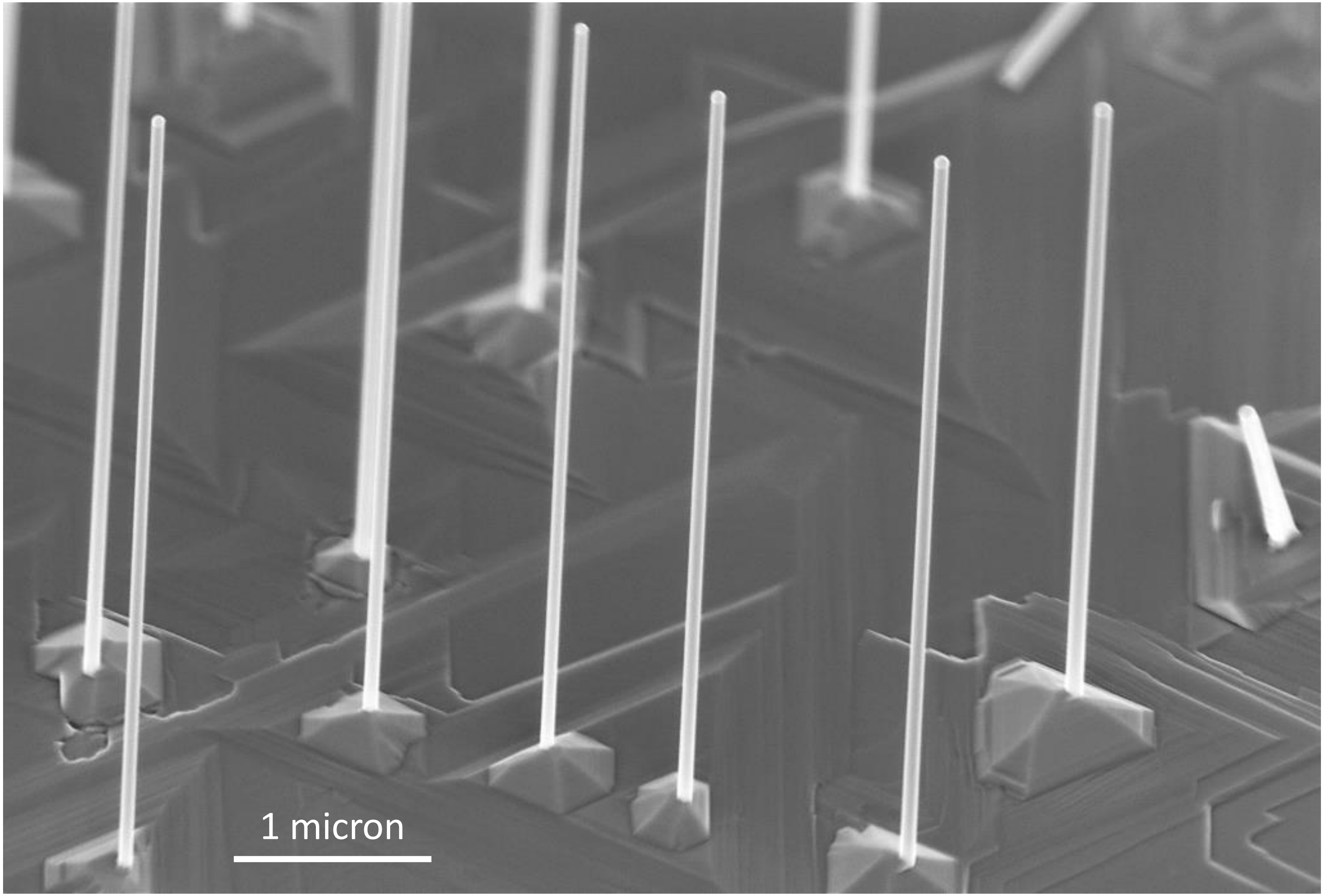
Doping n=10^{16} -10^{19} cm^{-3}

Density and diameter control

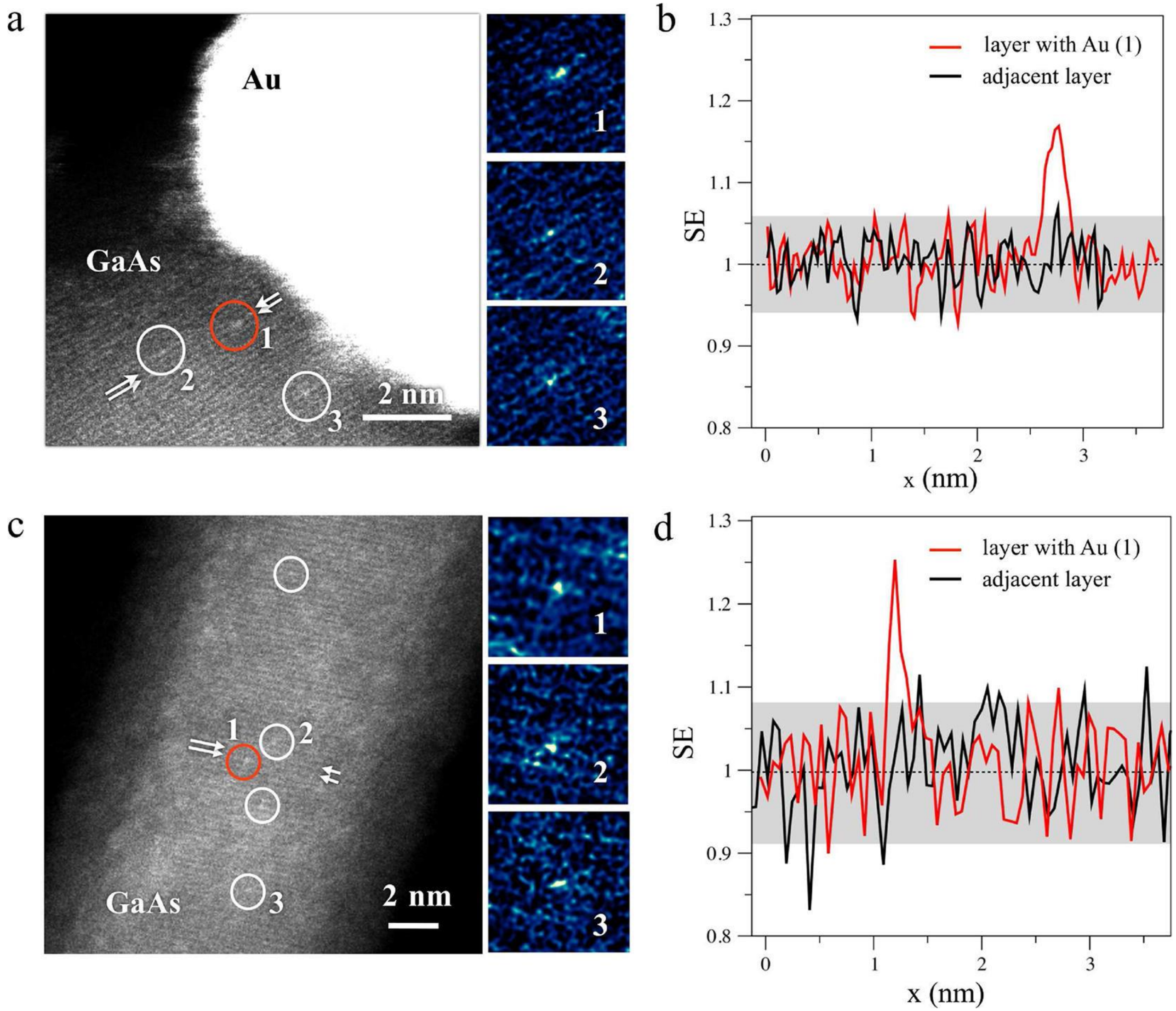


U. Gomes et al., Semicond Sci Tech 30, 010301 (2015).

Au-assisted InAs NWs on 111B InAs



Possible gold incorporation



HR HAADF images

Maya Bar-Sanan et al. Nano Lett. **12**, 2352 (2012)

Moving to self-assisted growth of InAs NWs

Gold suspected to incorporate

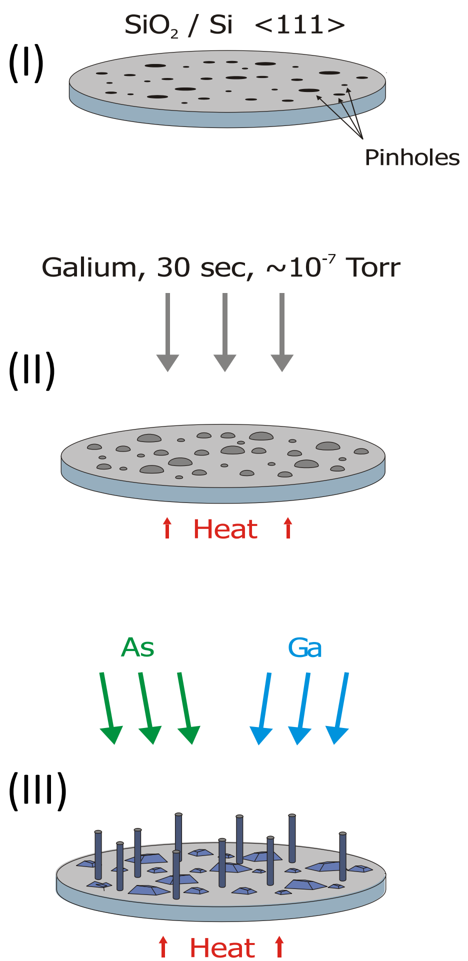
- scatter electrons

Self-assisted growth

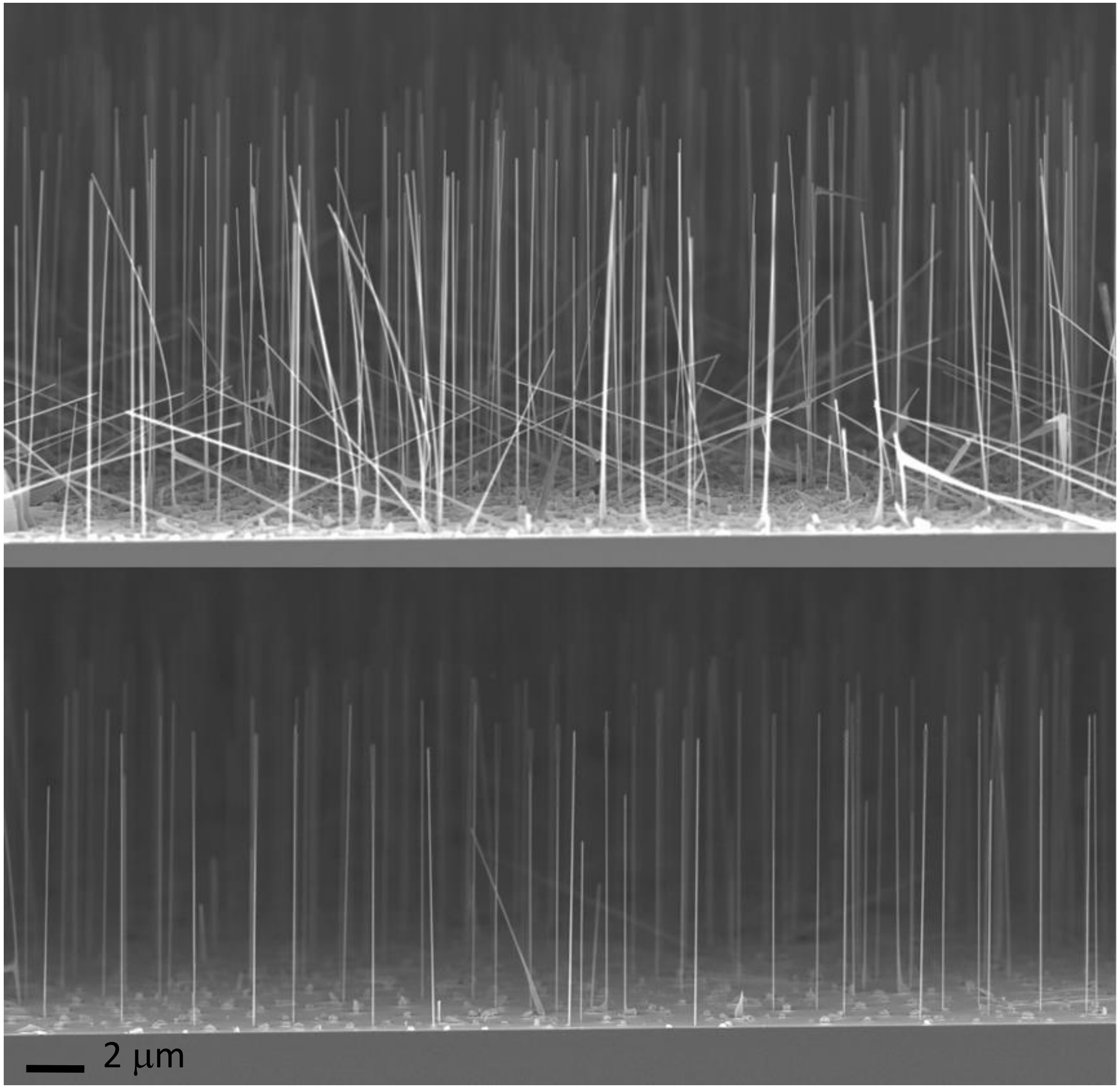
Simple/direct process

In-situ metallization

Self-Assisted GaAs NWs on SiO_2/Si

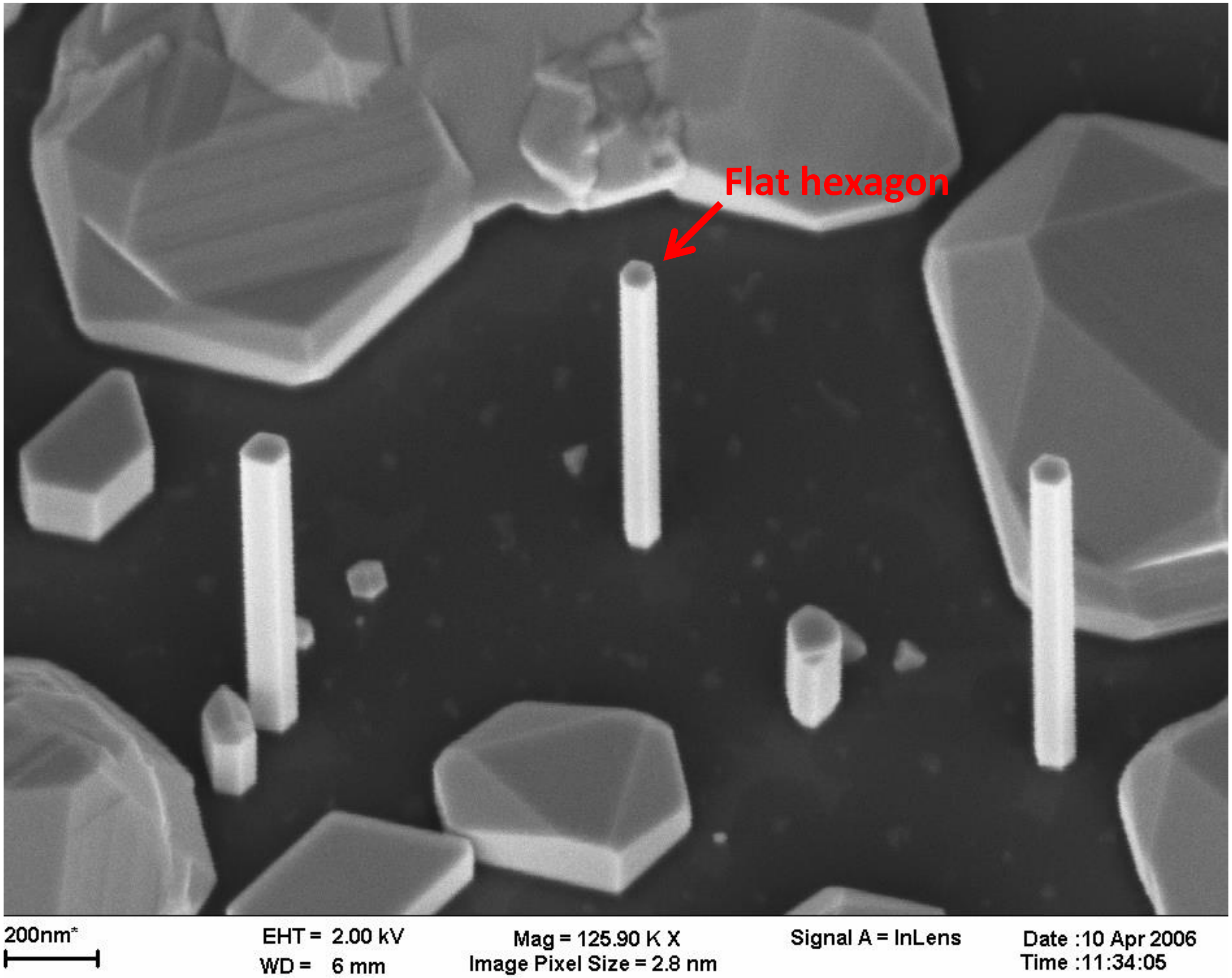


Following A. Fontcuberta i Morral, et. al., Appl. Phys. Lett. 2008



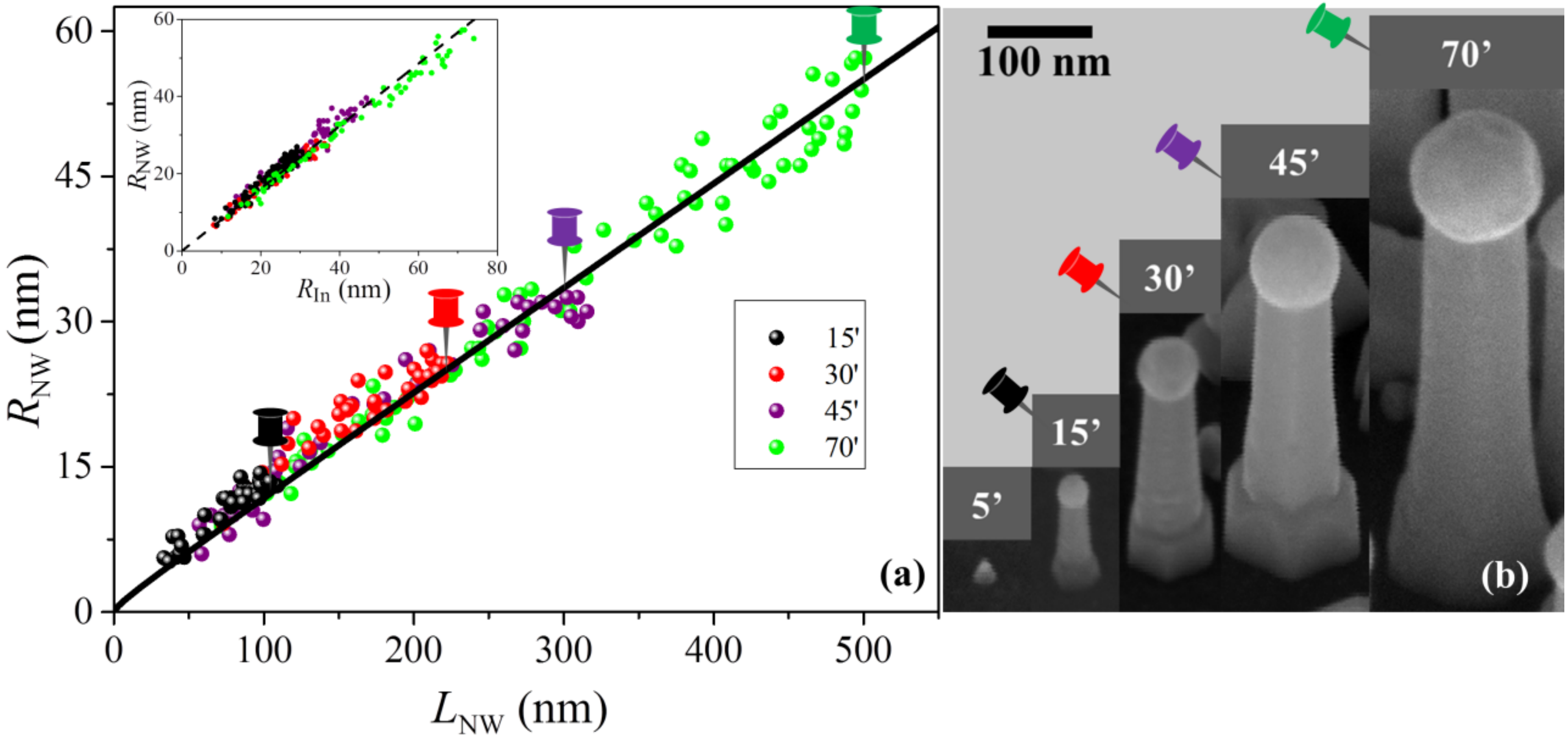
Peter Krogstrup et al., Nano Lett. **10**, 4475 (2010)

Self-assisted InAs NWs on Si/SiO2



Many groups have published works on such NWs mostly low aspect ratio
Example: Julich; PDI; Munich

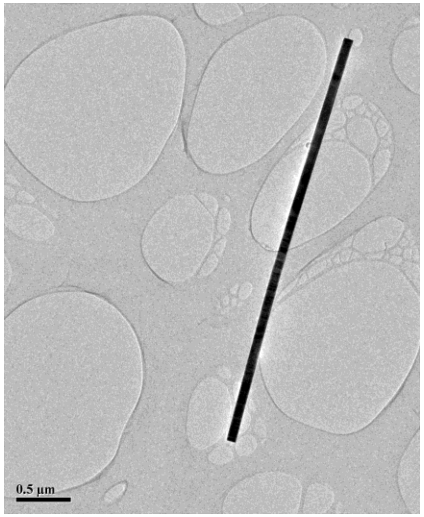
Self-assisted InAs NWs on 111 Si

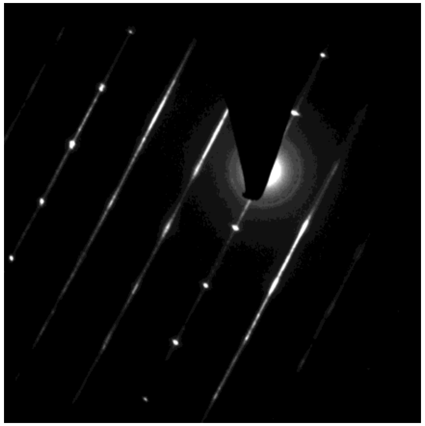


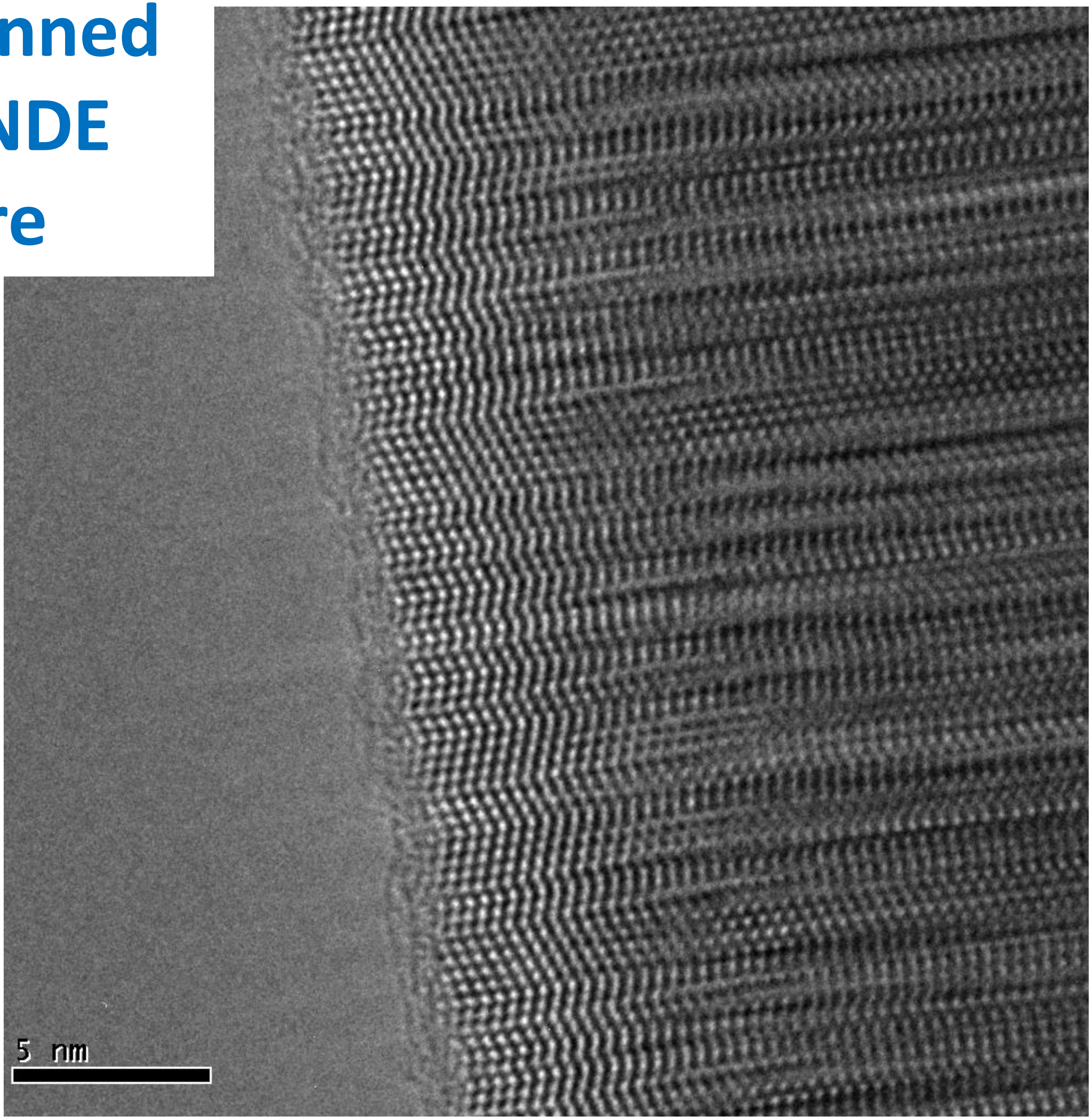
InAs NWs continue to nucleate on the Si (111) surface causing a spread in the NW size distribution

U. Gomes et al. Nanotechnology (2016) in press

Typical Twinned ZINC BLENDE structure







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Self-assisted InAs NWs on graphene

Structural compatibility of honeycomb crystal lattice with the ZB and WZ of many III-V NWs

Graphene a new substrate material:

Excellent electrical & mechanical properties

Optical transparency

Fabrication of semiconductor/graphene hybrid structures

via van der Waals epitaxy

A. Mazid Munshi, Nano Lett., 12 4570 (2012) GaAs NWs by MBE on graphite and SLG
Young Joon Hong, Nano Lett., 12 1431 (2012) InAs NWs by MOCVD on SLG and MLG /SiO2

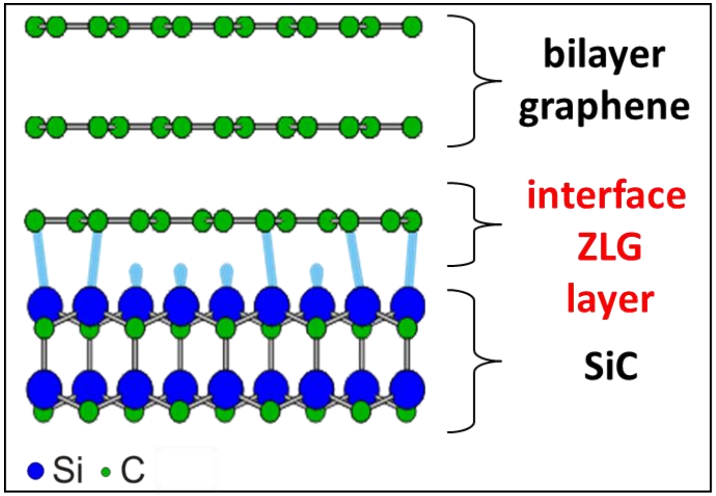
Role of the of graphene

Investigation on the morphology and crystal structure of InAs NWs:

- Bilayer graphene

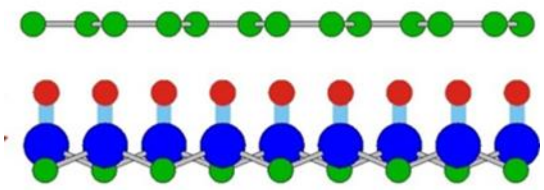
- Zero layer graphene (buffer layer)

Graphene layers are grown by termal decomposition of Si-face of SiC(0001) at 1350-1380 °C in Ar atmosphere



- Hydrogen intercalated of ZLG (quasi free standing graphene)

Annnealing at 600-900 °C in pure H

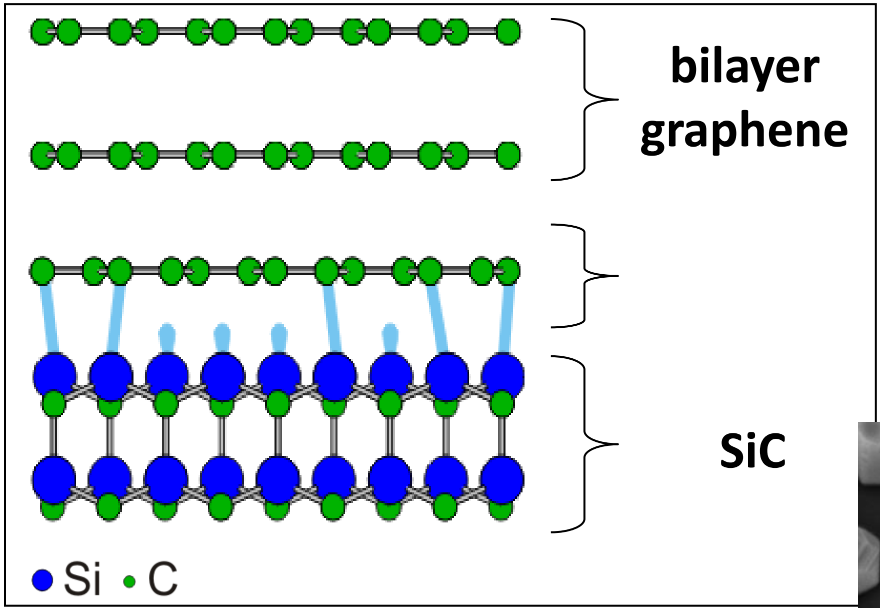


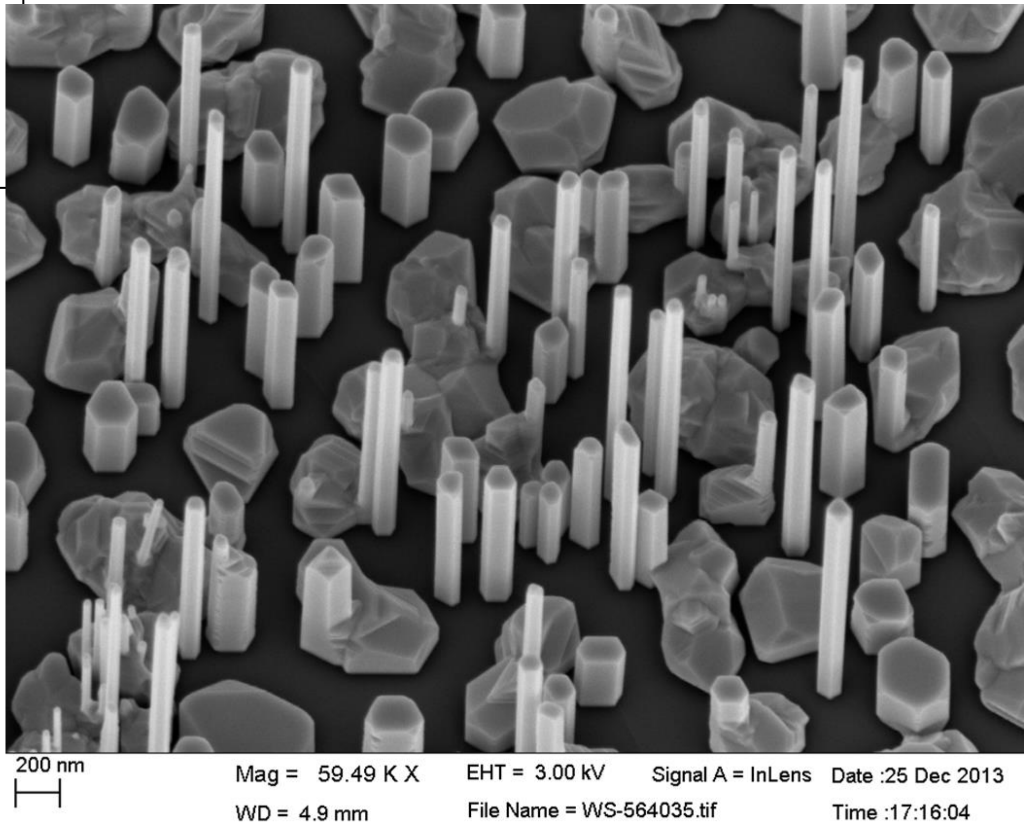
QFSZLG

=> Different surface corrugation

J.H. Kang et al., submitted

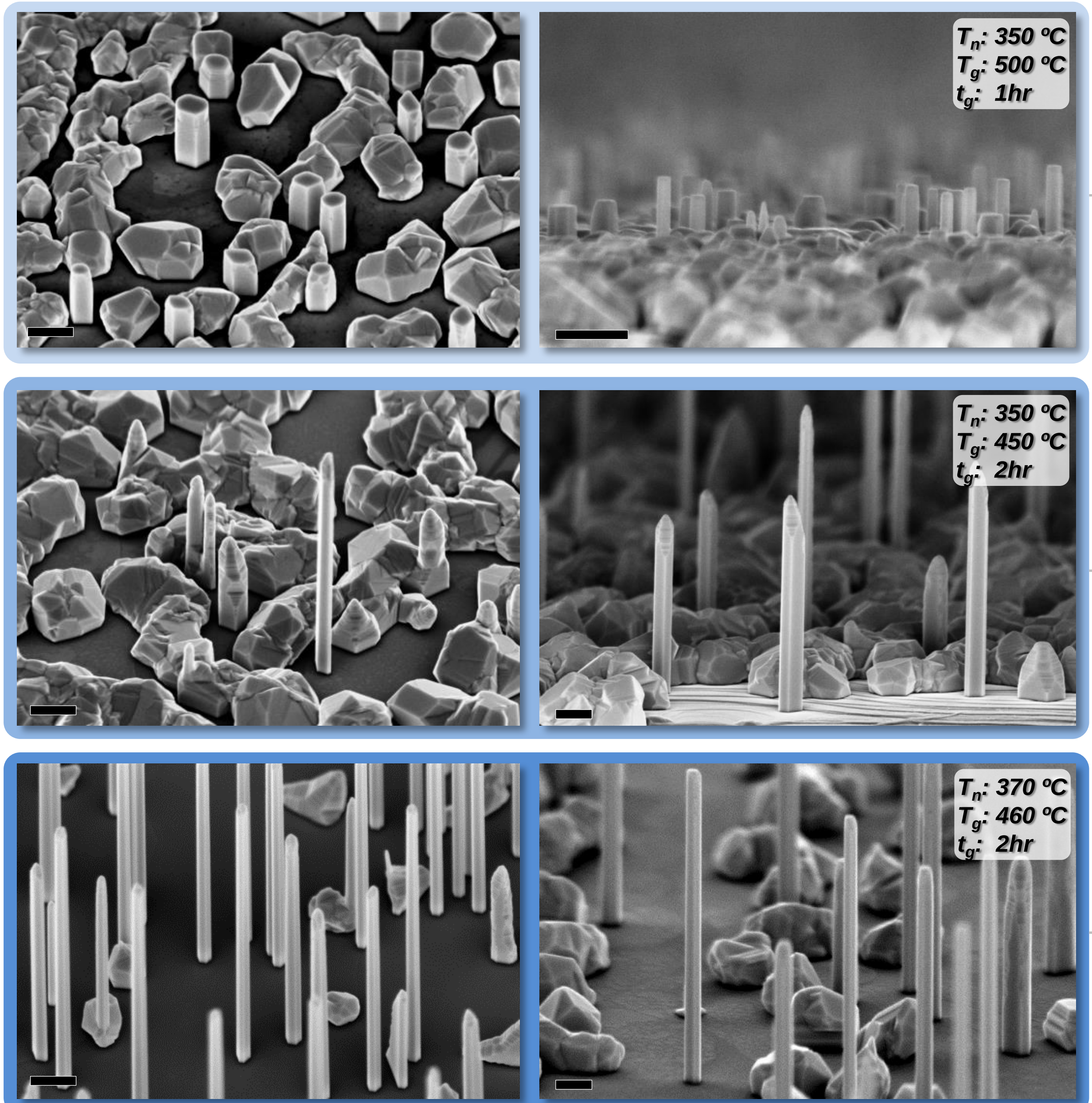
InAs NWs on bilayer Graphene on SiC(0001):





- Low aspect ratio
- Flat top
- Significant side growth

Improved NWs density & aspect ratio



**All scale bars: 400 nm*

- D: 100~400 nm
- L: 0.17~0.4 μm

x2 growth time
lower growth temperature

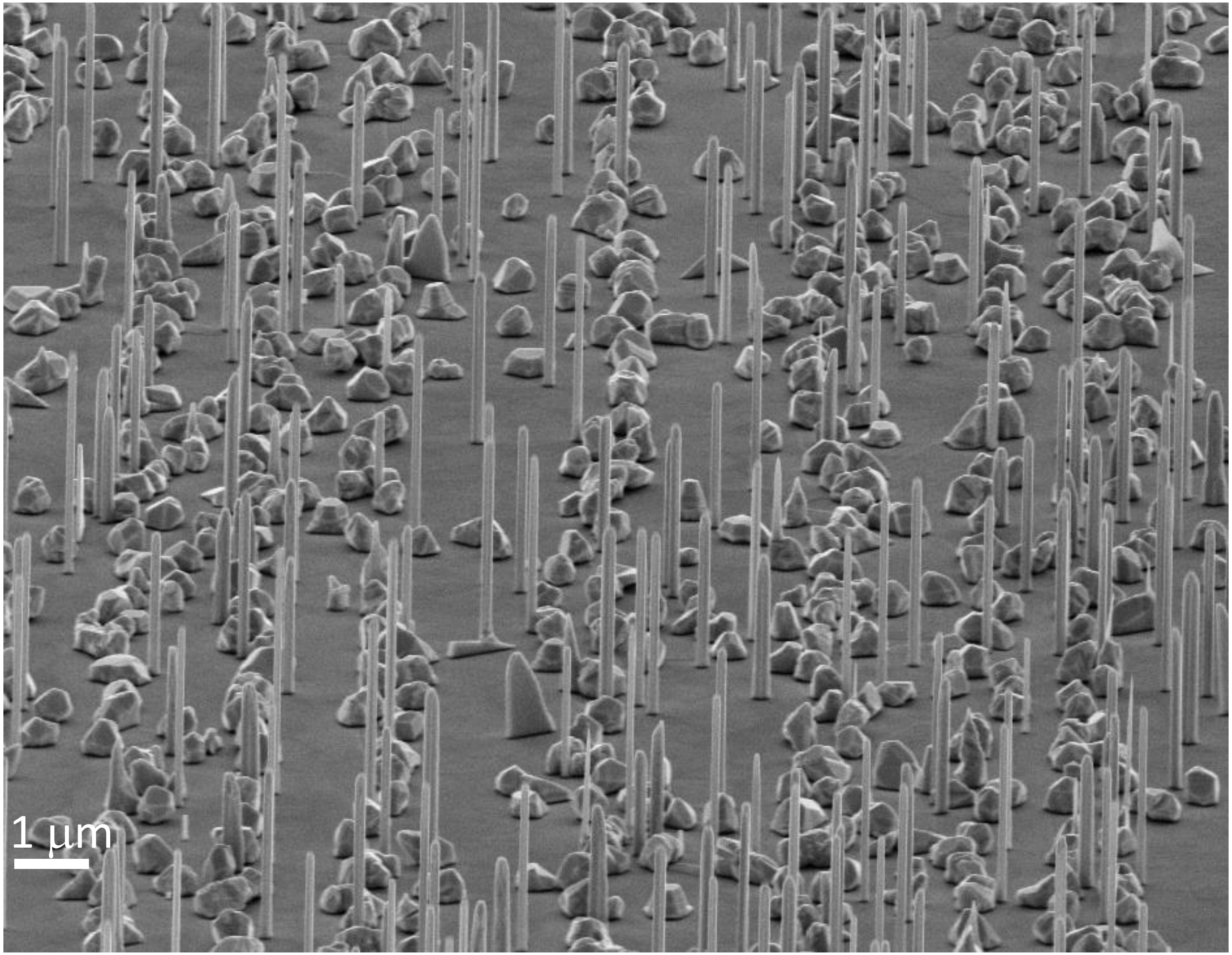
- D: 150~160 nm
- L: 3.2~5.8 μm

lower indium
higher nucleation temperature

- D: 120~180 nm
- L: 3.5~4.5 μm

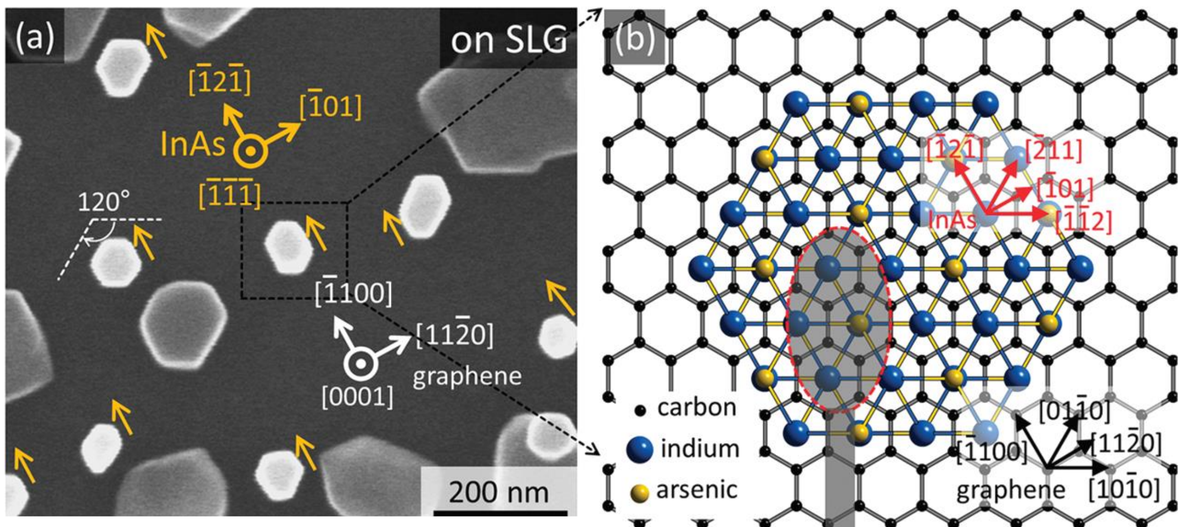
Improved density & length

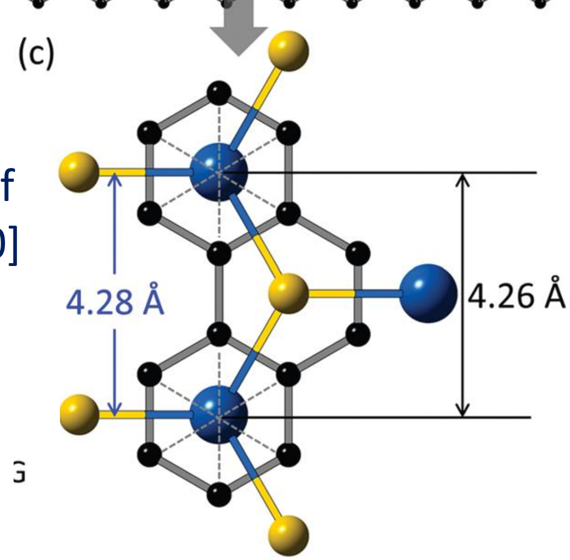
Aspect ratio about 25



All NWs well aligned at 90° to the bilayer graphene substrate

Positioning of self-assisted InAs NWs on SL graphene

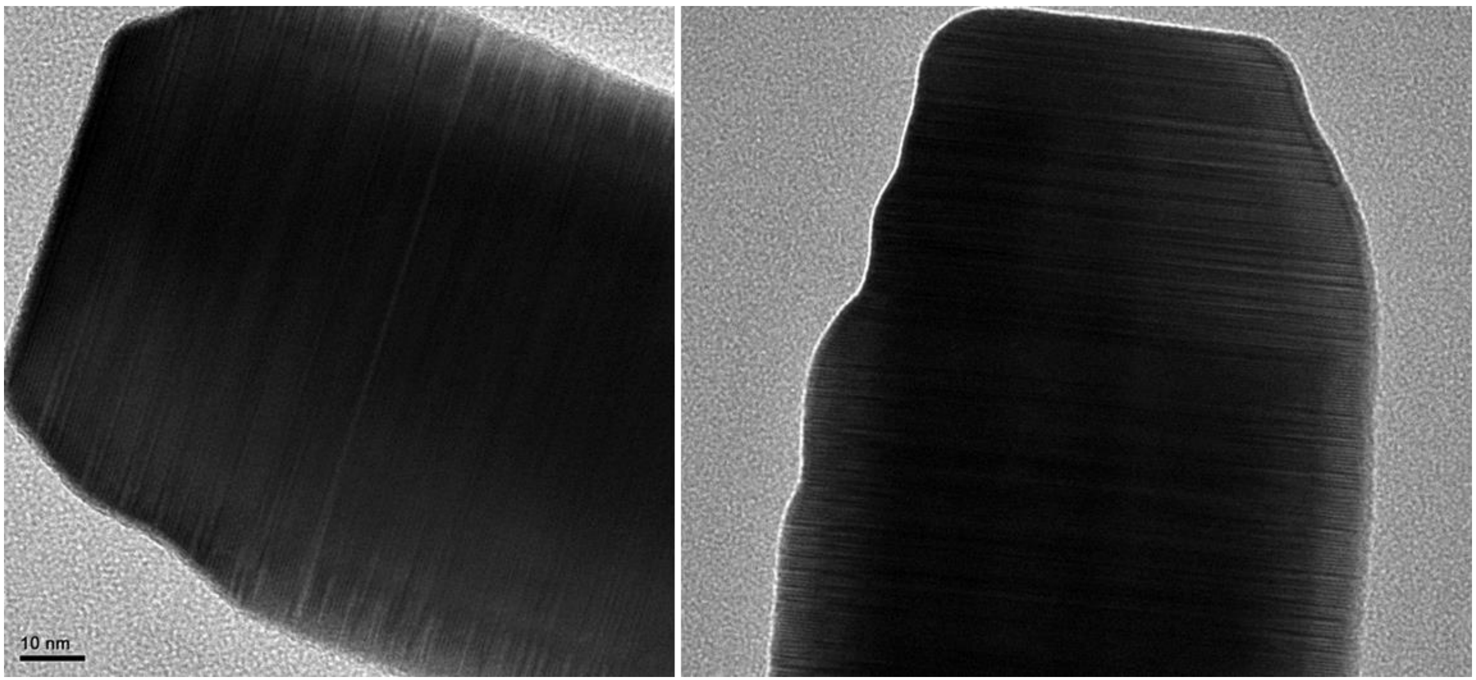




Nearly coherent heteroepitaxial relationship of zinc blende InAs-(1̄1̄1̄)[1̄10]||SLG-(0001)[12̄10]

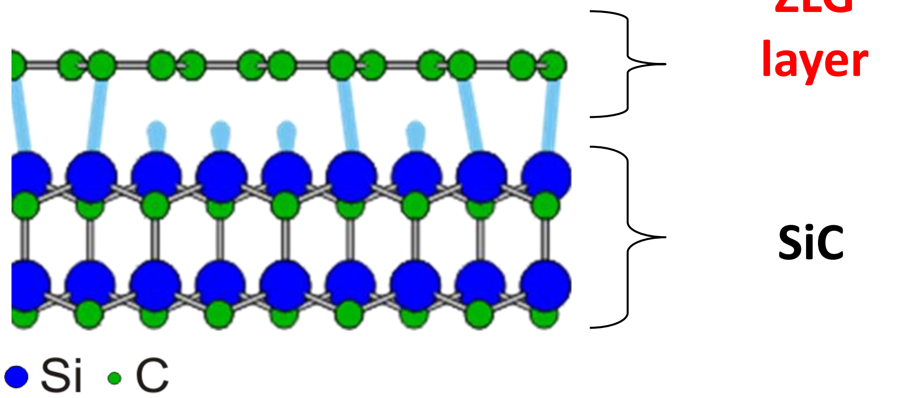
Young Joon Hong et al., Nano Lett. 12, 1431 (2012)

TEM of InAs NWs on Bilayer Graphene

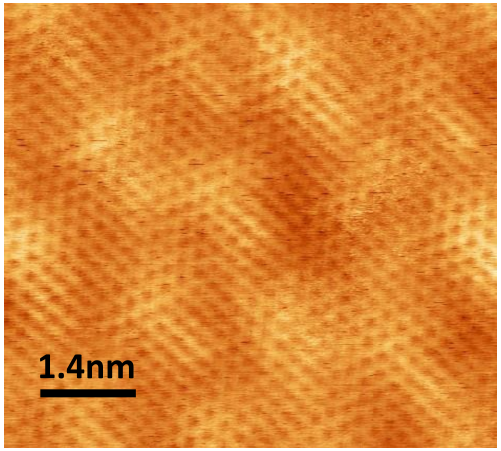


Mixed WZ&ZB structure

Improving NW aspect ratio on buffer (ZLG)



STM



Honeycomb atomic structure of the ZLG
S. Goler, C. Coletti, et al., Carbon 51 (2013)

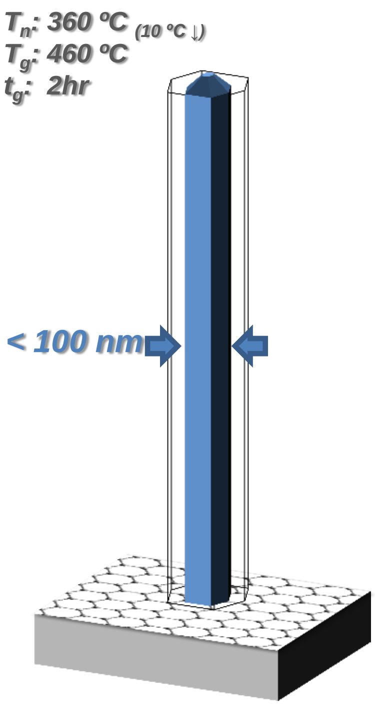
Interface (buffer/zero) layer :

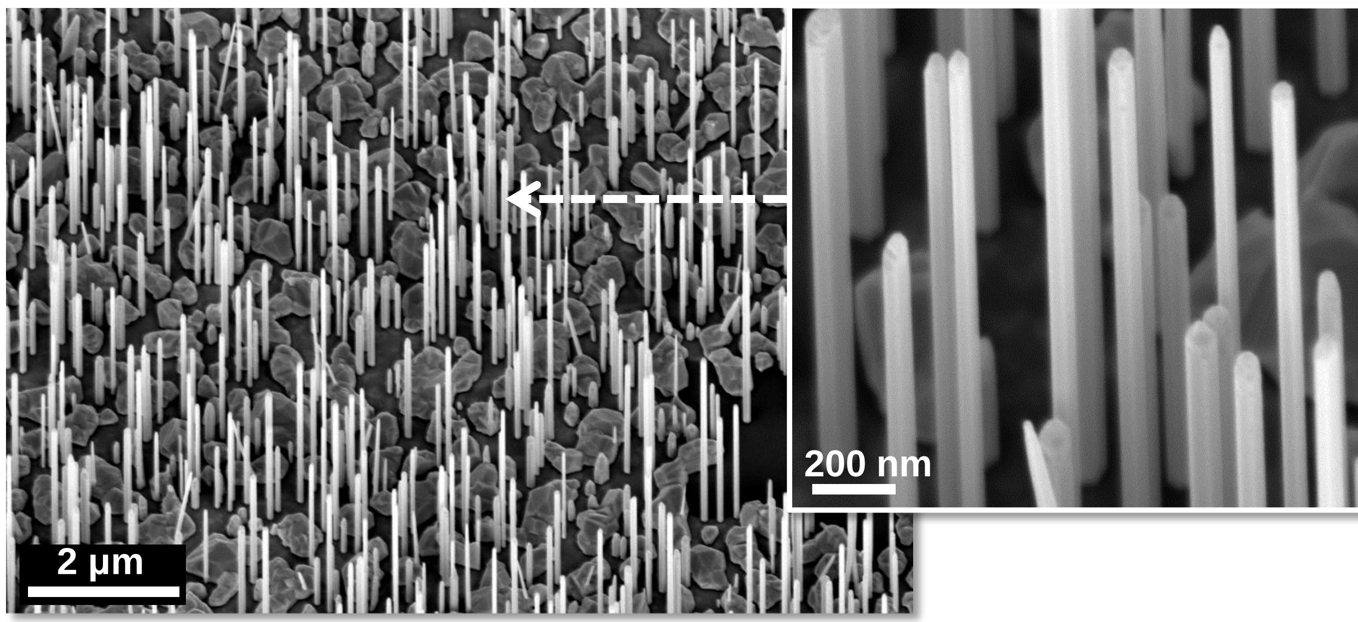
- Highly corrugated surface -> shorter diffusion length -> metallic clusters with smaller diameter
- Carbon atoms disposed in a graphene-like honeycomb lattice $(6\sqrt{3}x6\sqrt{3})$ 30° reconstruction

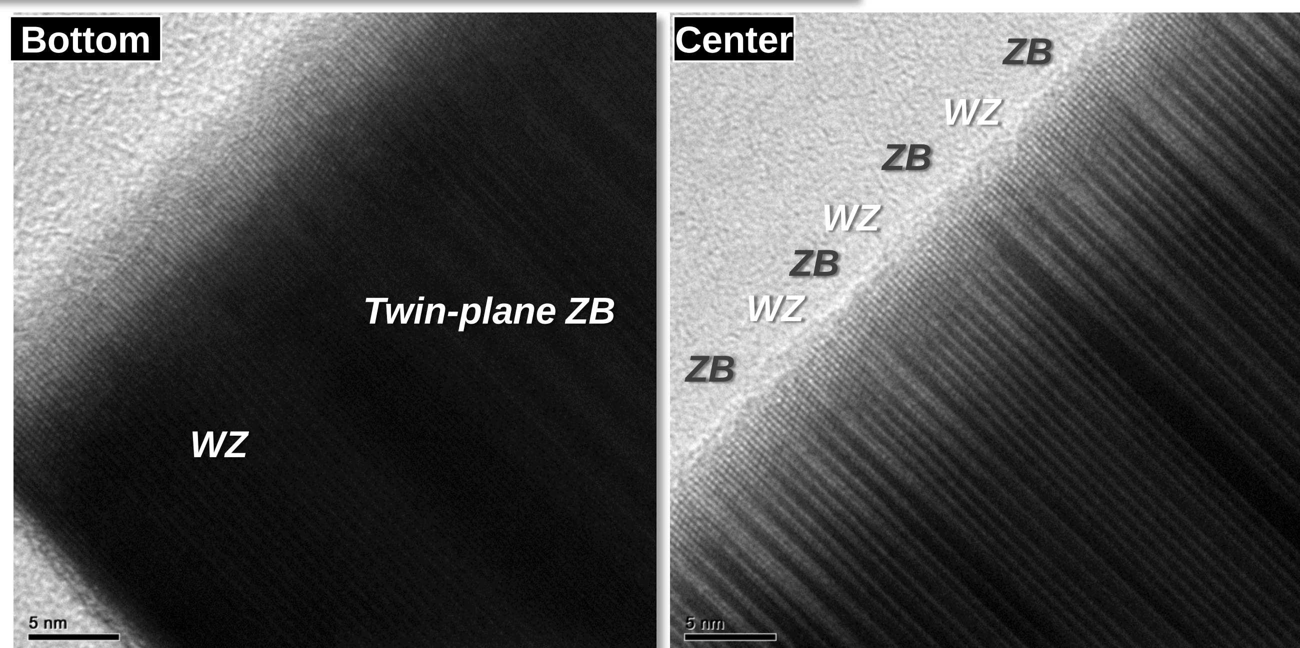
Improving NWs aspect ratio by growth on ZLG

Morphology

Thinner NWs





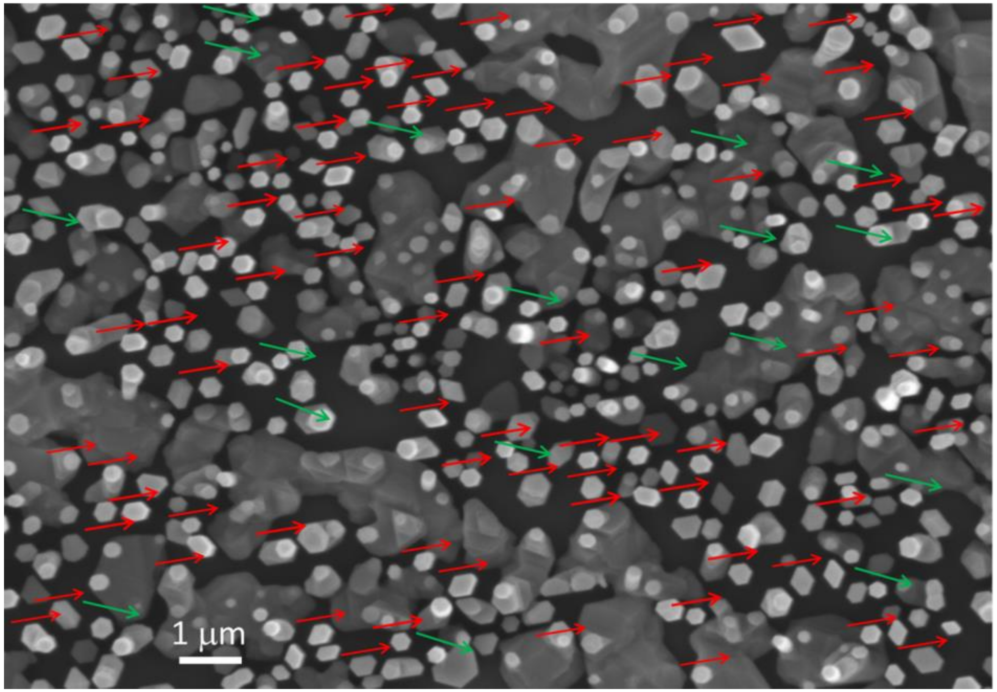


D: 60~70 nm

L: 3.5~4.7 µm

Mixed WZ&ZB structure

InAs NW orientation



10% InAs NWs grown on a buffer (ZLG) graphene   oriented by 30°

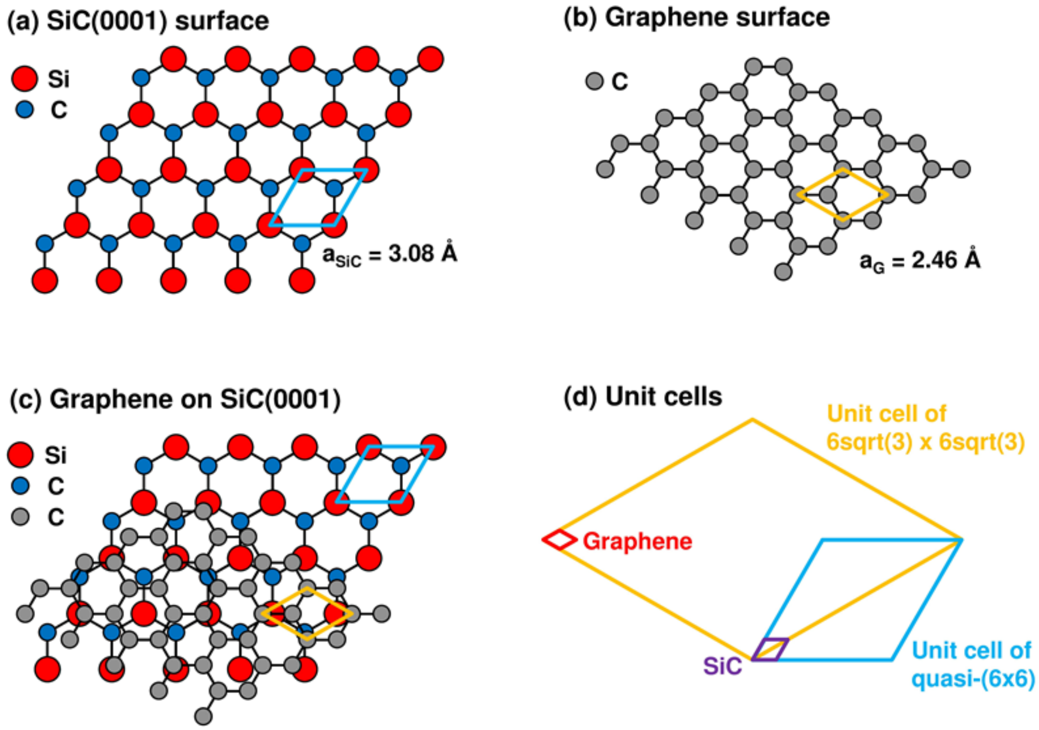
Possible reasons for NW rotation

1. Graphene crystallinity

Epitaxial growth on Si-face of SiC (LEED , STM)

2. Partially covered SiC substrate

no InAs NWs on SiC



Possible reasons for NW rotation

3. Deviation from values of lattice constants

- InAs Lattice constant matches with the 0 ° configuration (for 30° lattice constant of InAs -> 5.25 Å instead of 6 Å)

- Thermal expansion leads only to small variations

		Lattice Constant, *a* (Å)		
		Configuration 30º	Configuration 0º	InAs
RT	Buffer Layer	5.224	6.033	6.0583
	Bilayer Graphene	5.224	6.033	
400 ºC	Buffer Layer	5.230	6.040	6.0693
	Bilayer Graphene	5.207	6.014	

- Buffer layer compressive strain of 0.8% with respect to SiC

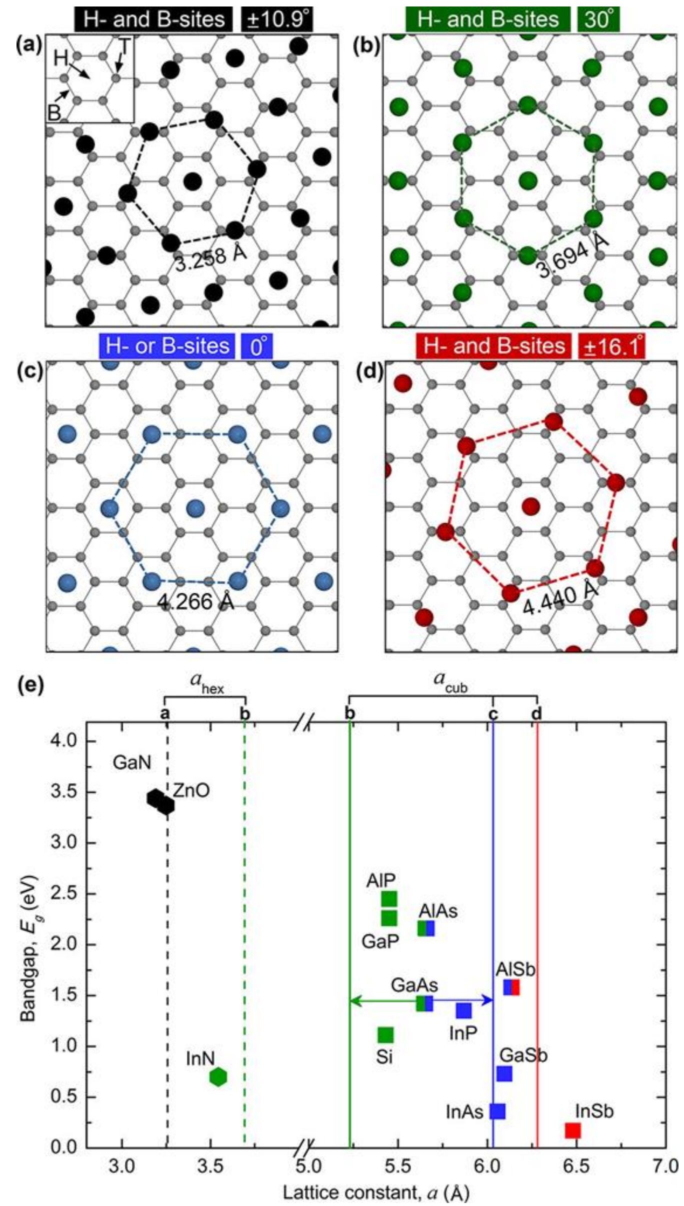
  Strain ±1%

  buffer layer 30° [5.172 Å, 5.276 Å]

  0° [5.973 Å, 6.093 Å]

  InAs [5.998 Å, 6.119 Å]

  bilayer even less strain

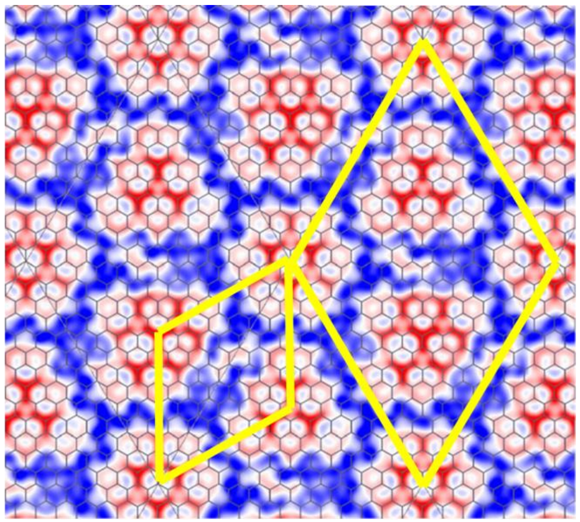


A. Mazid Munshi et al. , Nano lett. 2012, 12 4570

Possible reasons for NW rotation

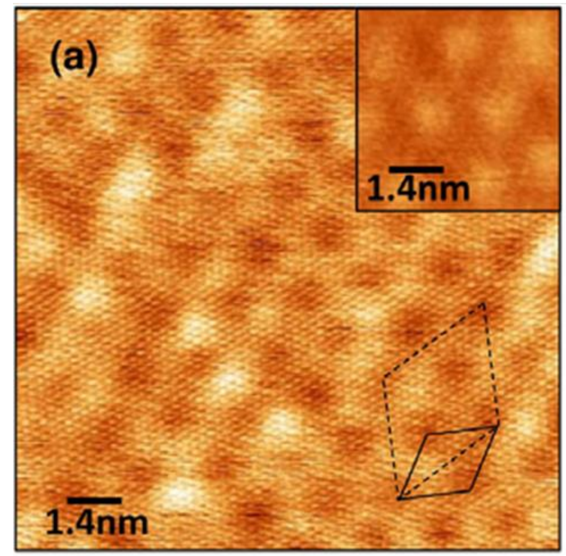
4. InAs NWs rotation follows the surface corrugation of the graphene buffer layer

30°



6×6 $\quad$ $6\sqrt{3} \times 6\sqrt{3}$

Image from J. Sforzini et al., Phys. Rev. Lett. 114, 106804 (2015).



S. Goler et al. Carbon 51, 249 (2013)

InAs NWs follow the quasi (6x6) unit cell (i.e. they grow aligned with the surface corrugation) of the buffer layer

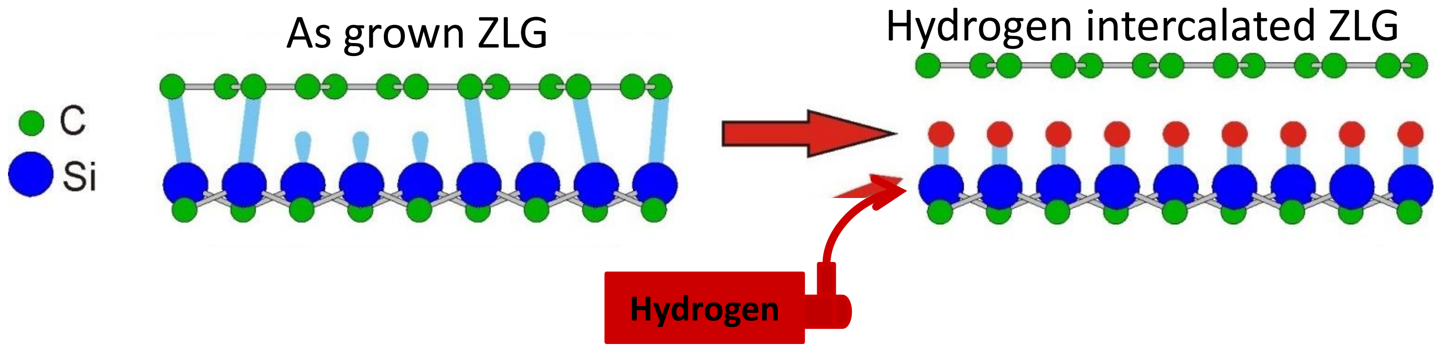
Cell length 6x6 (6x 3.08 Å SiC) = 18.48 Å

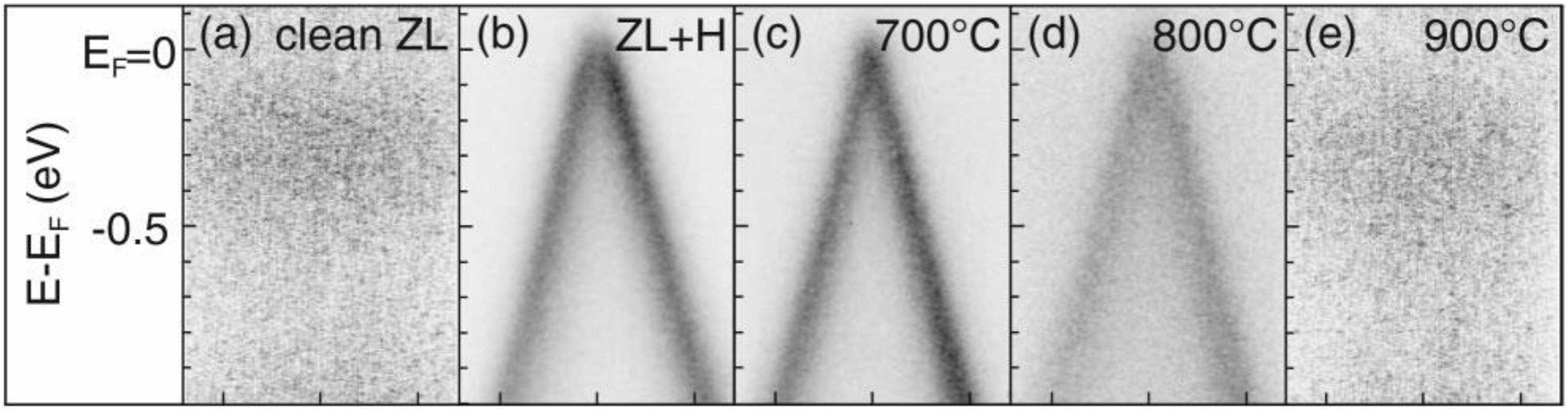
a(InAs) =6.0583Å/sqrt(2) = 4.284Å X 4 = 17.1 Å

In order to test this hypothesis we have grown InAs NWs on uncorrelated/flat surface

Hydrogen intercalation of ZLG (QFMLG)

Method: annealing at 600°C – 900°C in an atmosphere of ultra-pure H_2 gas

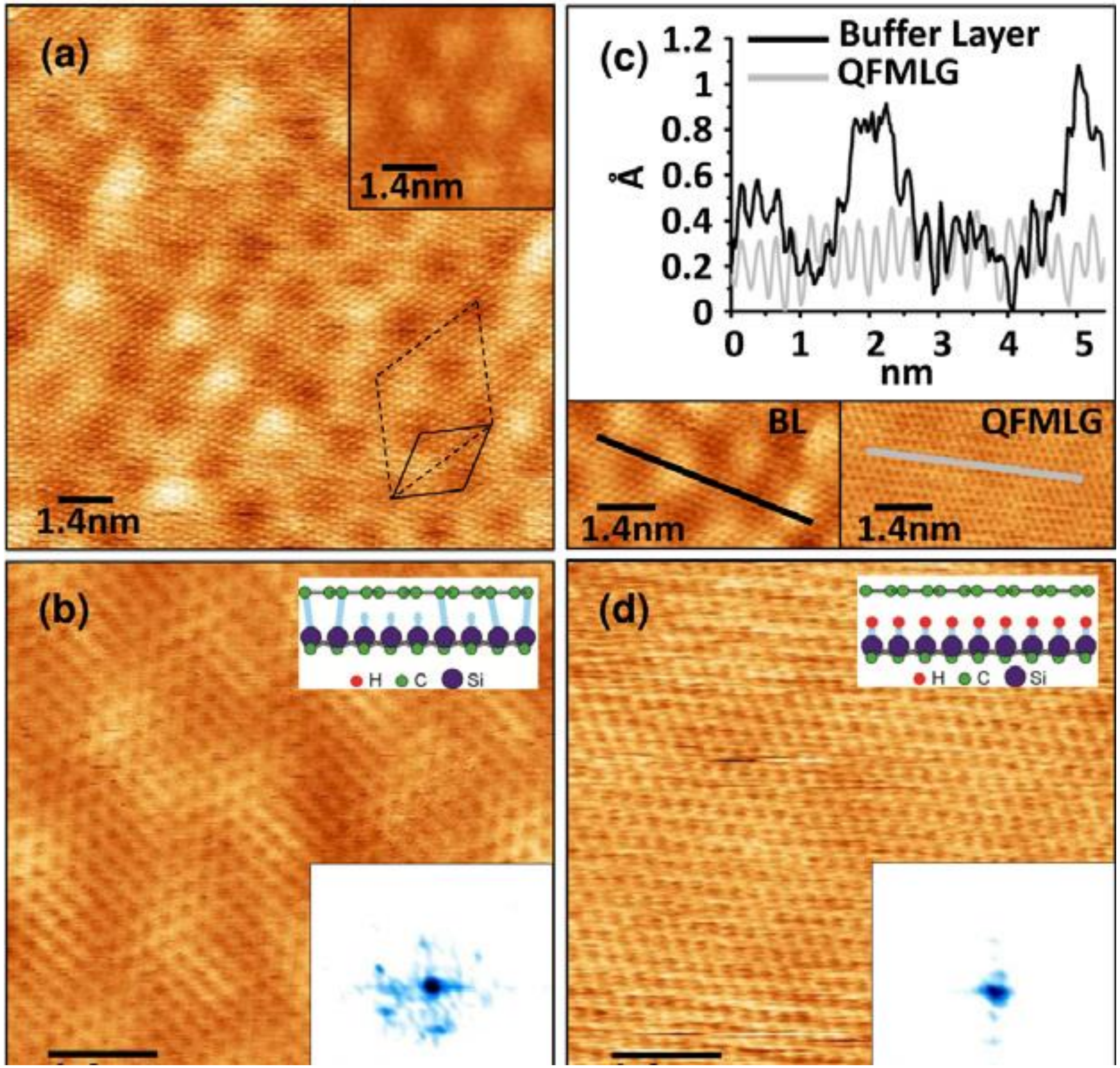




Yields FLAT quasi-free standing ZLG

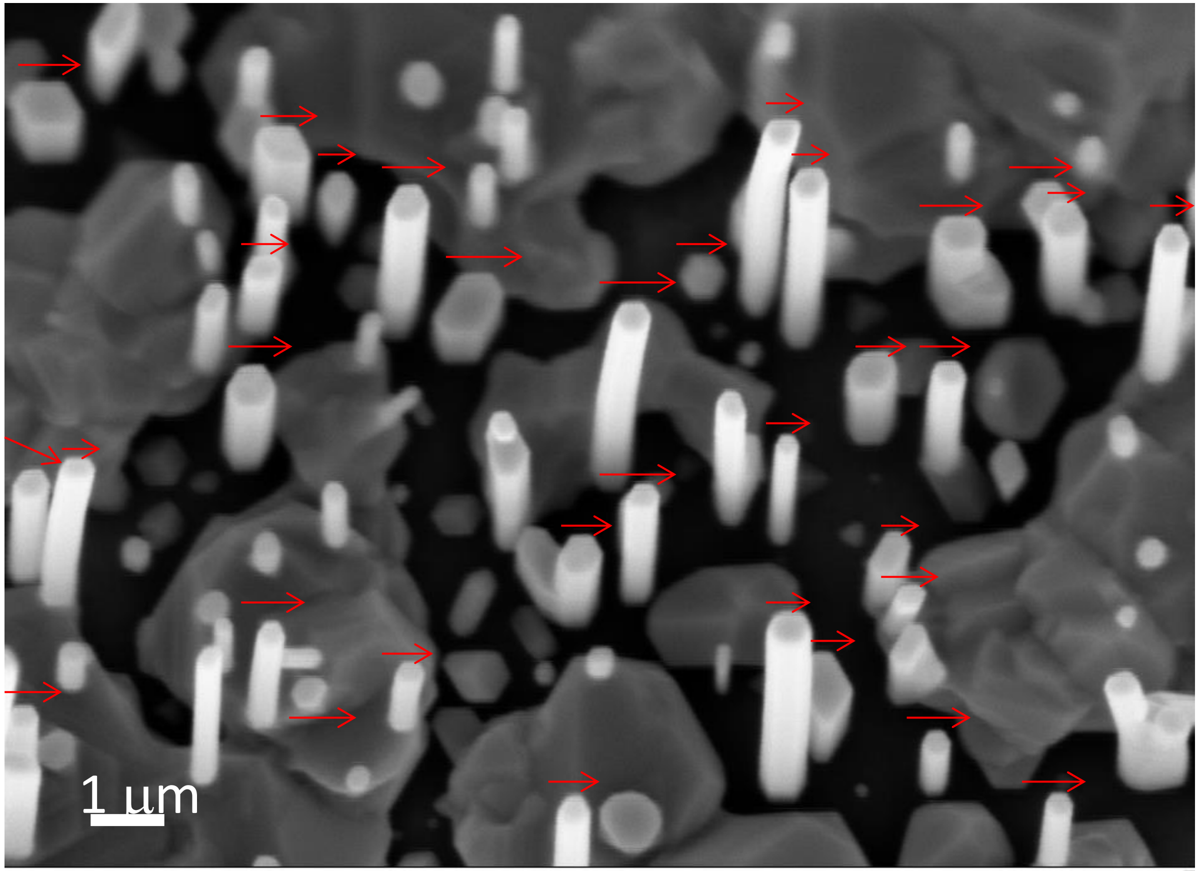
C. Riedl et al. Phys. Rev. Lett. **103**, 246804 (2009)

Corrugation of buffer layer vs H intercalated (QFMLG)



Sarah Goler et al. Carbon 51, 249 (2013)

InAs NWs alignment on H intercalated (QFMLG)



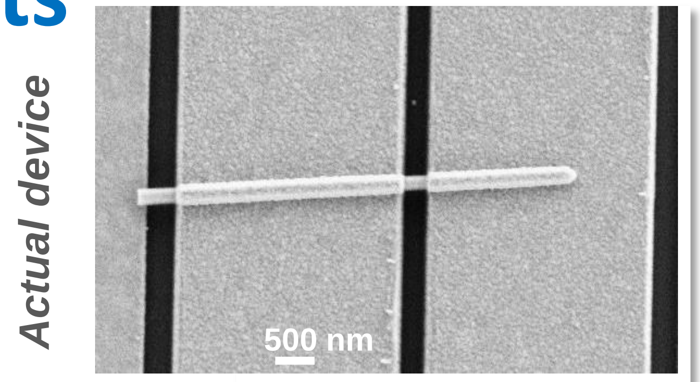
100% of InAs NWs are fully aligned !!

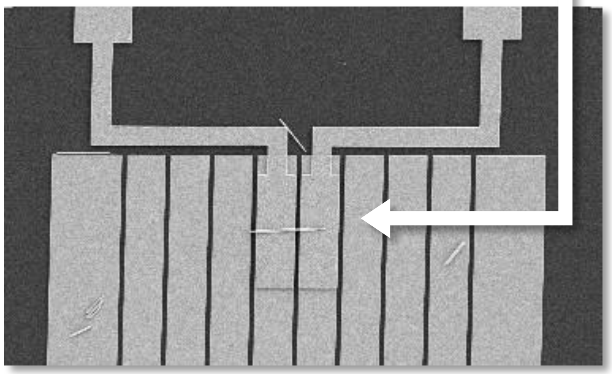
We now understand that surface roughness plays an important role on the InAs NW orientation.

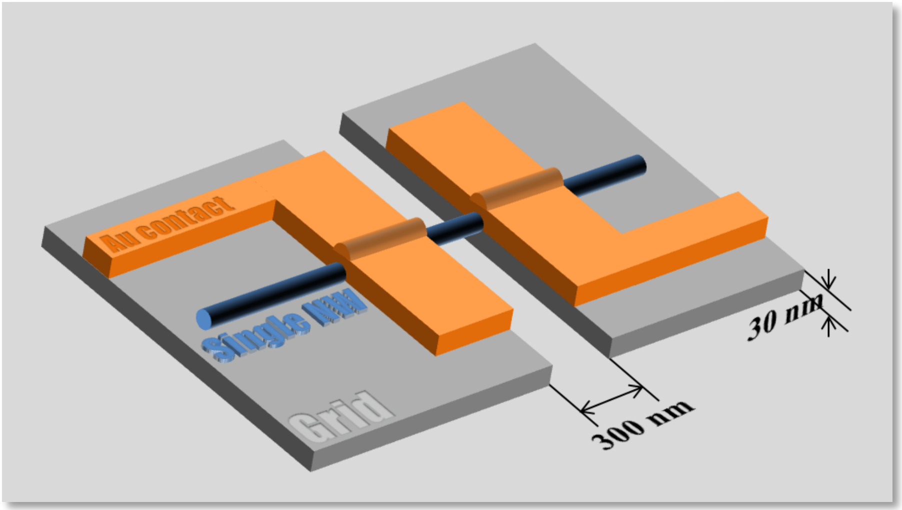
Conductance measurements

The NW surface etched by ammonium sulfide to remove the oxide and facilitate formation of Ohmic contacts.

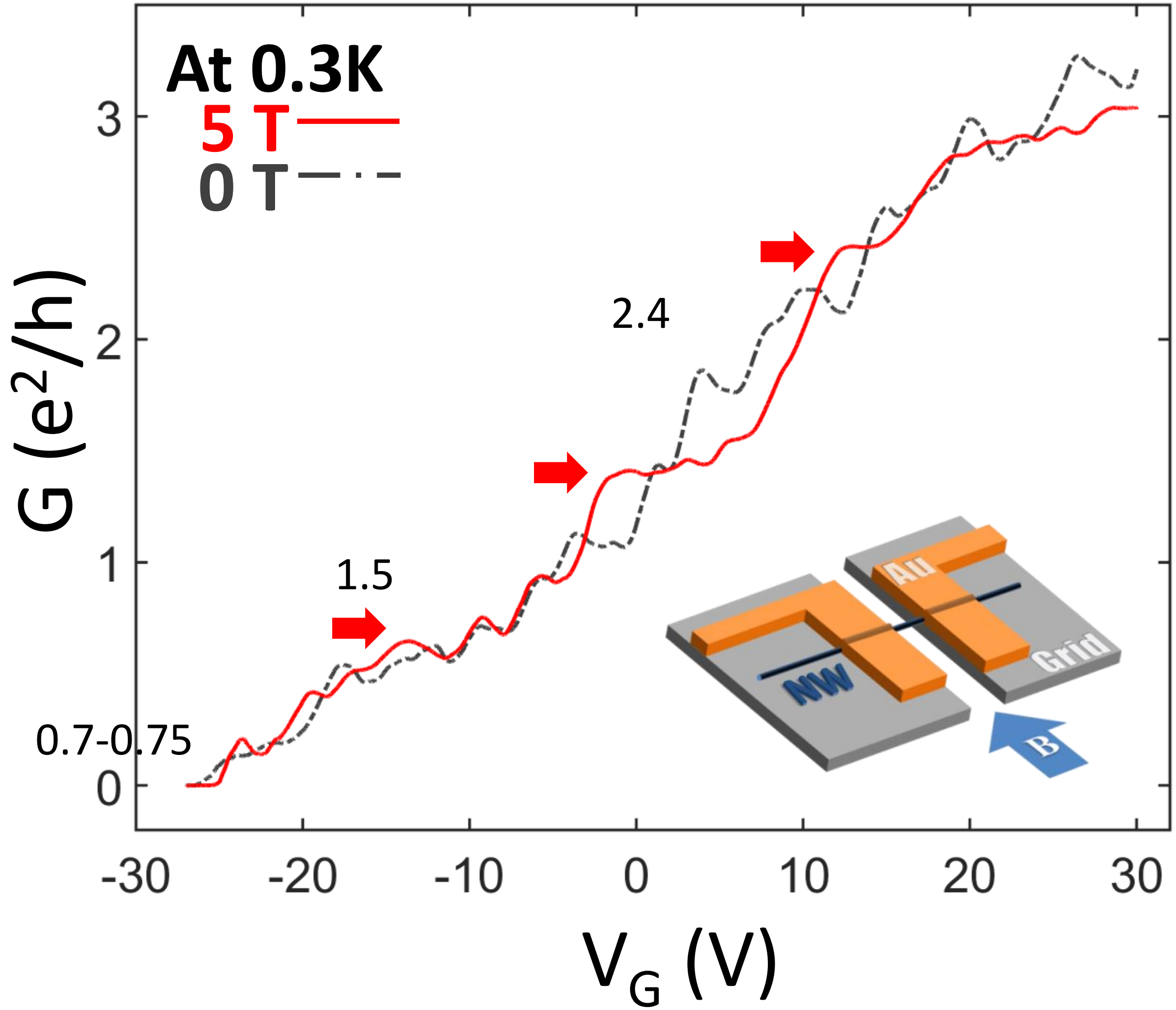
The NW is suspended 30 nm above the surface.







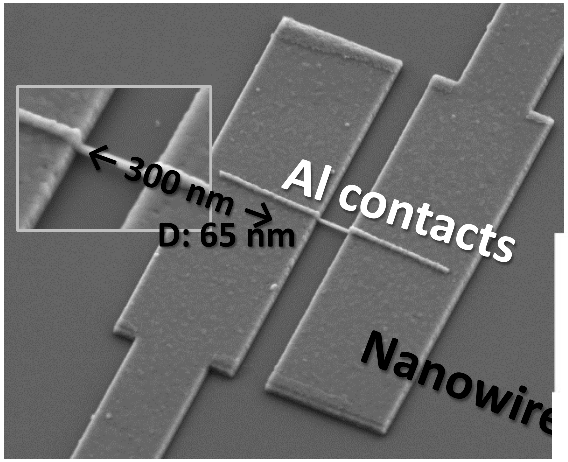
Conductance (G) as a function of gate voltage (V_G) with/without magnetic field



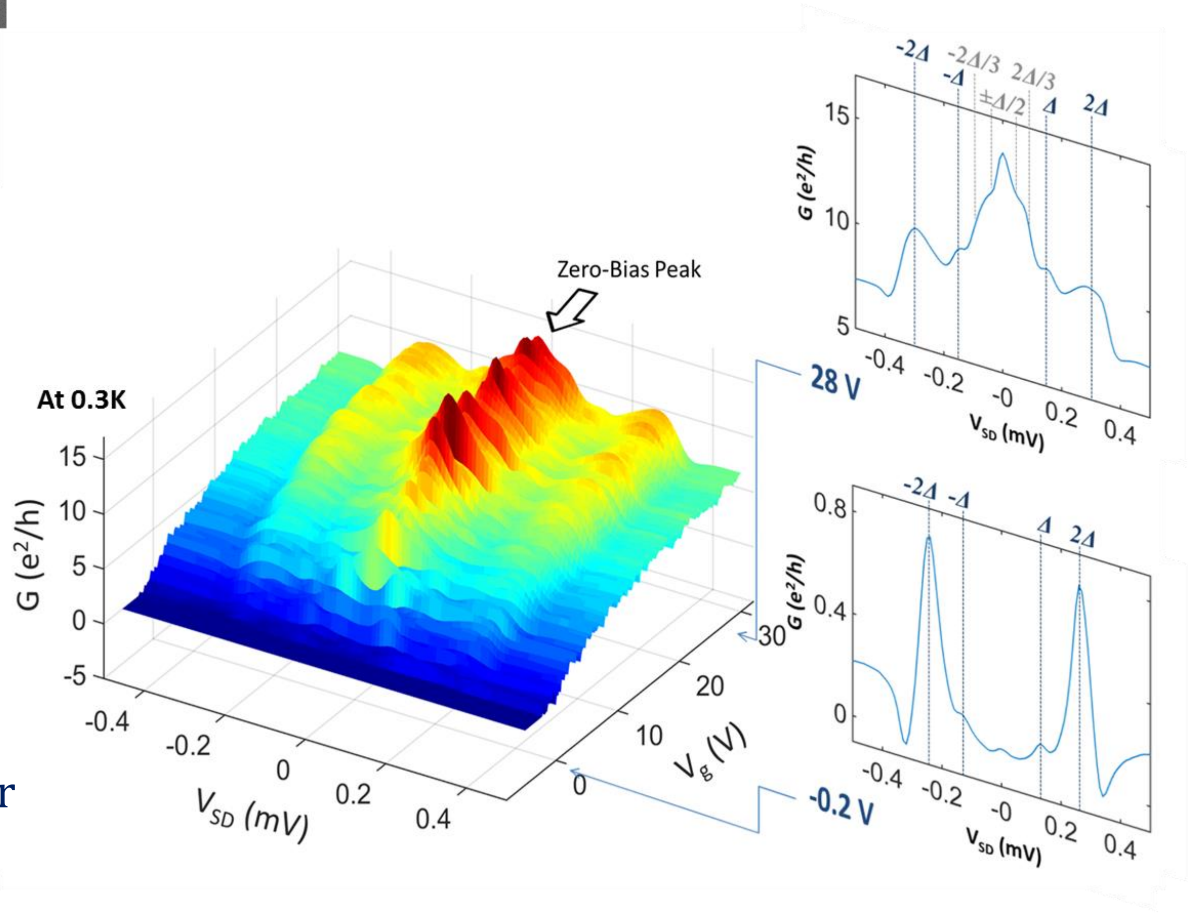
Ballistic regime -> conductance plateaux

The magnetic field minimizes the electron backscattering due to the crystal defects

Superconducting Josephson junction device of single InAs NW



3D scanning image of Multiple-Andreev Reflection (MAR)



Multiple reflections of quasi particles

Inelastic scattering length $\sim 900\ nm$ 3rd MAR order

Conclusions

- Reconstructed buffer (ZL) graphene is the best substrate and InAs NWs with best aspect ratio are realised

- Over 10% of InAs NWs grown buffer (ZL) graphene are oriented by 30° while on QFML graphene are aligned to the single facet direction.

- The 30° orientation of the InAs Nws is due to the buffer corrugation (quasi 6x6 reconstruction)

- Despite many twin planes LT transport measurements demostrated good electronic properties:

  observation of conductance steps

  superconductivity with symmetric multiple Andreeev reflection peaks.

Collaboration

- Hadas Shtrikman
- Jung-Hyun Kang
- Yuval Ronen
- Yonatan Cohen
- Perla Kacman (*Institute of Physics, Warsaw, Poland)*

Condensed Matter Physics Department
of Weizmann Institute of Science

- Camilla Coletti
- Domenica Convertino
- Antonio Rossi

CNI@NEST
Istituto Italiano di Tecnologia

- Stefan Heun

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Pisa, Italy

References transport part

[1] Paschen F., Back E., 'Liniengruppen magnetisch vervollständigt', *Physica* 1921, **1**, 261–273.

[2] Weperen I. Vsn, Plissard S. R., Bakkers E. P. A. M., Frolov S. M., Kouwenhoven L. P., 'Quantized Conductance in an InSb Nanowires', *Nano Lett.* 2013, **13**, 387-391.

[3] Berggren K. F., Pepper M. 'Electrons in one dimension', *Phil. Trans. R. Soc. A* 2010, **368**, 1141-1162.

[4] Landauer R., 'Spatial variations of currents and fields due to localized scatterers in metallic conduction', *IBM J. Res. Dev.*, 1957. **1**, 223–231.

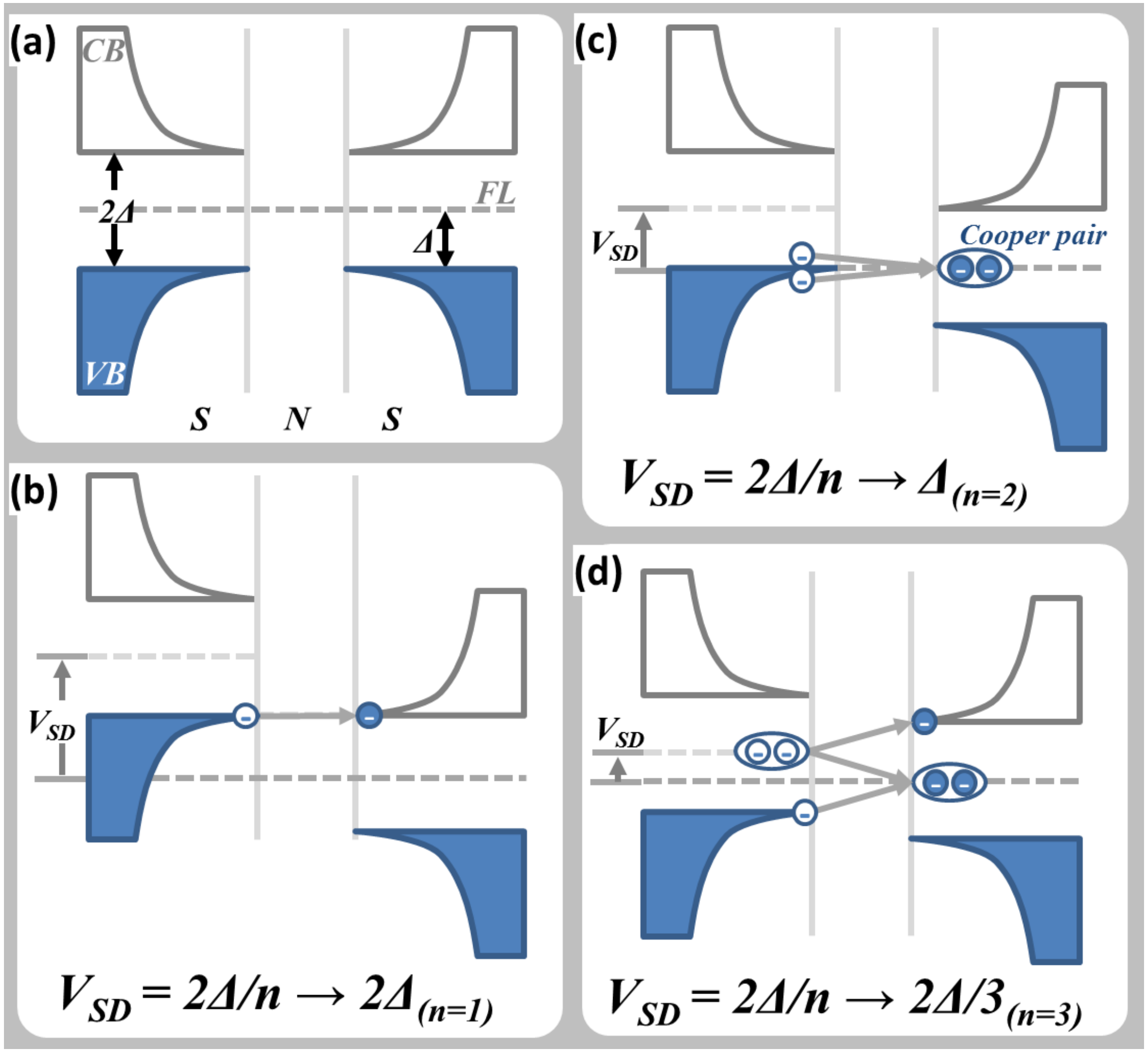
[5] Nazarov Y. V., Blanter Ya. M., 'Quantum transport: Introduction to Nanoscience', *Cambridge University Press* 2009, 29–41.

[6] Buitelaar M. R., Belzig W., Nussbaumer T., Babic B., Bruder C., Schonenberger C., 'Multiple Andreev Reflections in a Carbon Nanotube Quantum Dot', *Phys. Rev. Lett.* 2003, **91**, 057005.

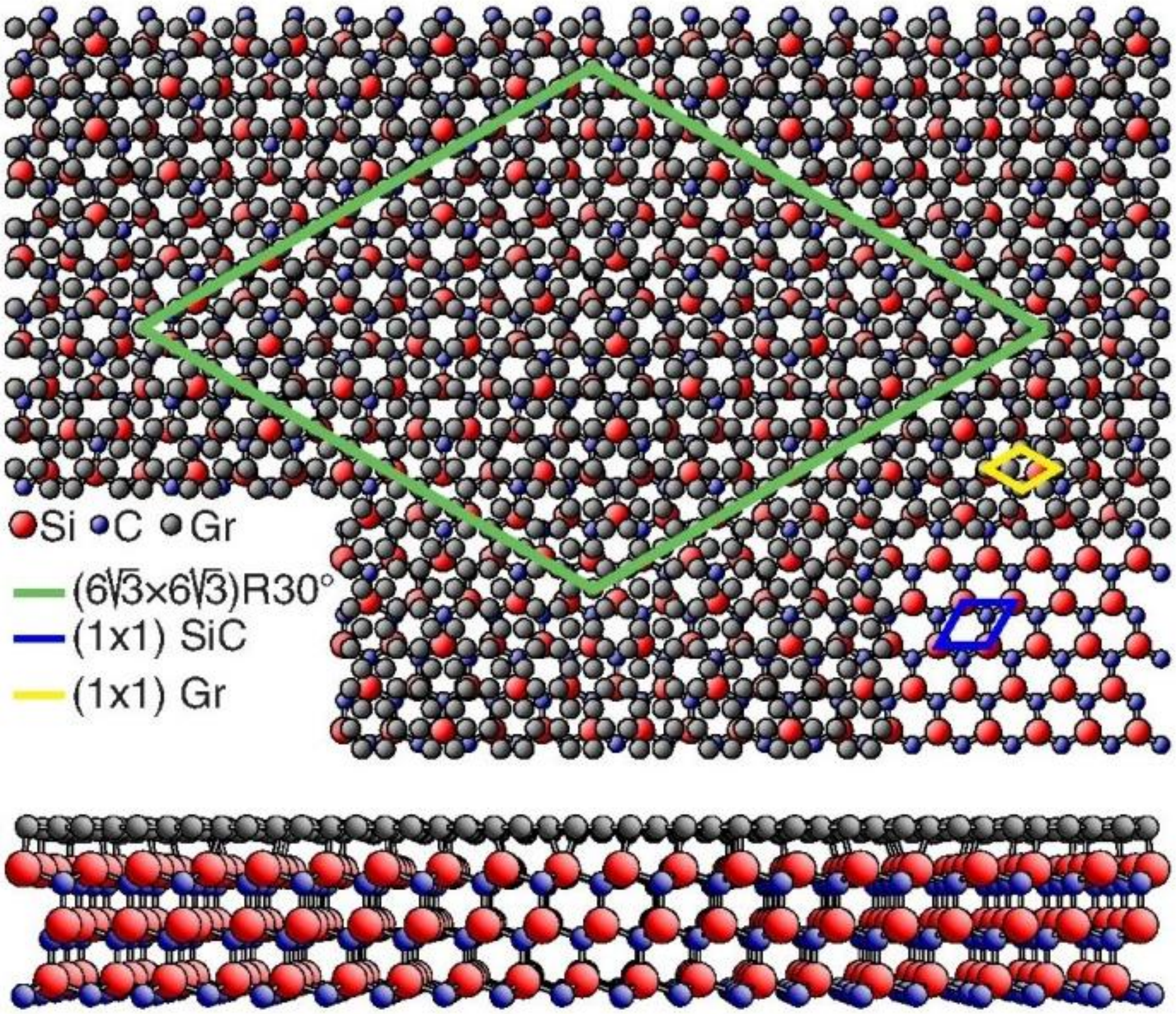
[7] Hoss T., Strunk C., Nussbaumer T., Huber R., Staufer U., Schonenberger C, 'Multiple Andreev reflection and giant excess noise in diffusive superconductor/normal-metal/superconductor junctions', *Phys. Rev. B* 2000, **62**, 4079-4085.

[8] Nilsson H. A., Samuelsson P., Caroff P., Xu H. Q., 'Supercurrent and Multiple Andreev Reflections in an InSb Nanowire Josephson Junction', *Nano Lett.* 2012, **12(1)**, 228-233.

Schematic images of the density of state (DOS) of the multiple-Andreev reflection (MAR)



Epitaxial Graphene on SiC



S Forti and U Starke, J. Phys. D: Appl. Phys. **47**, 094013 (2014)

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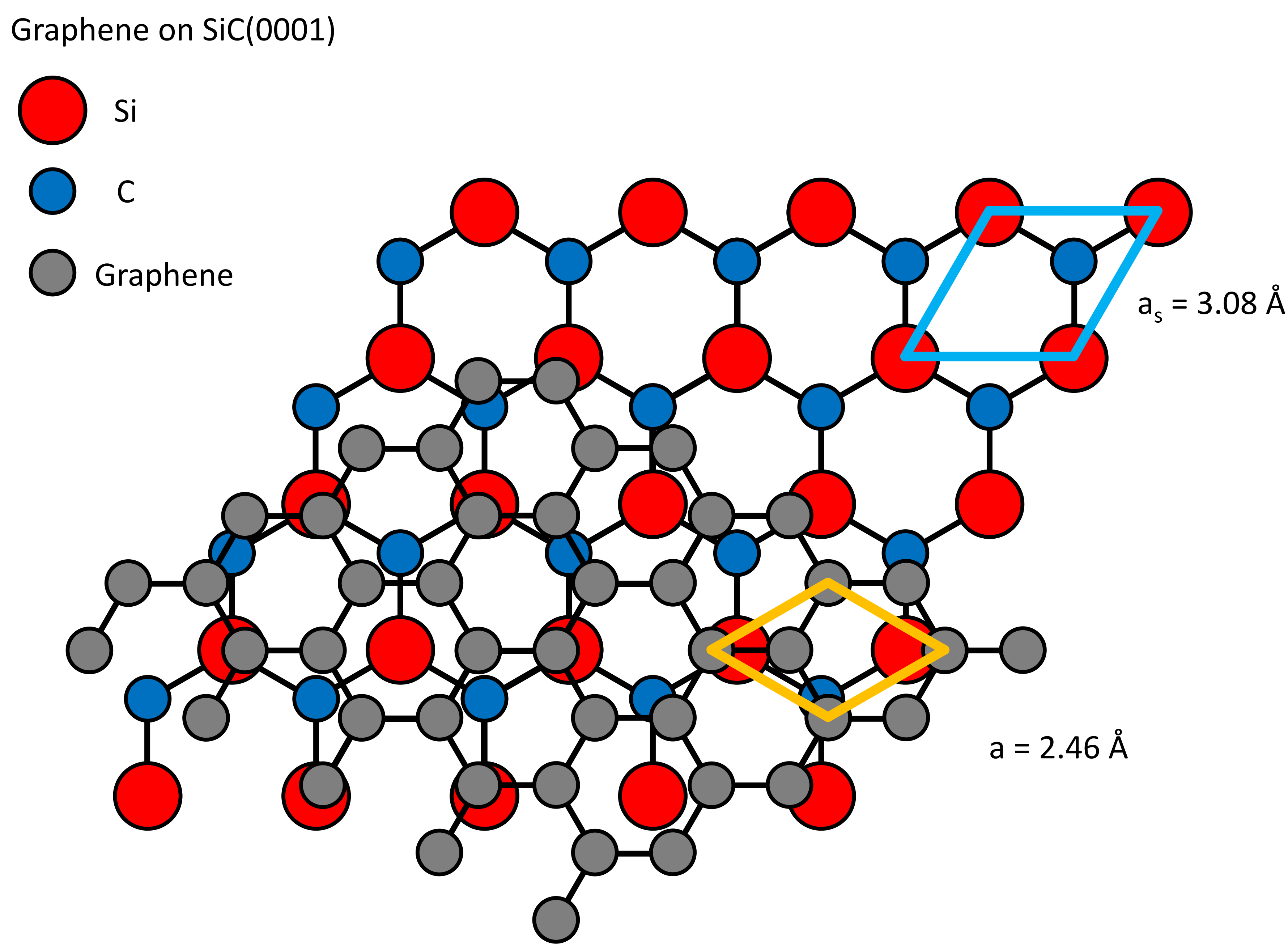
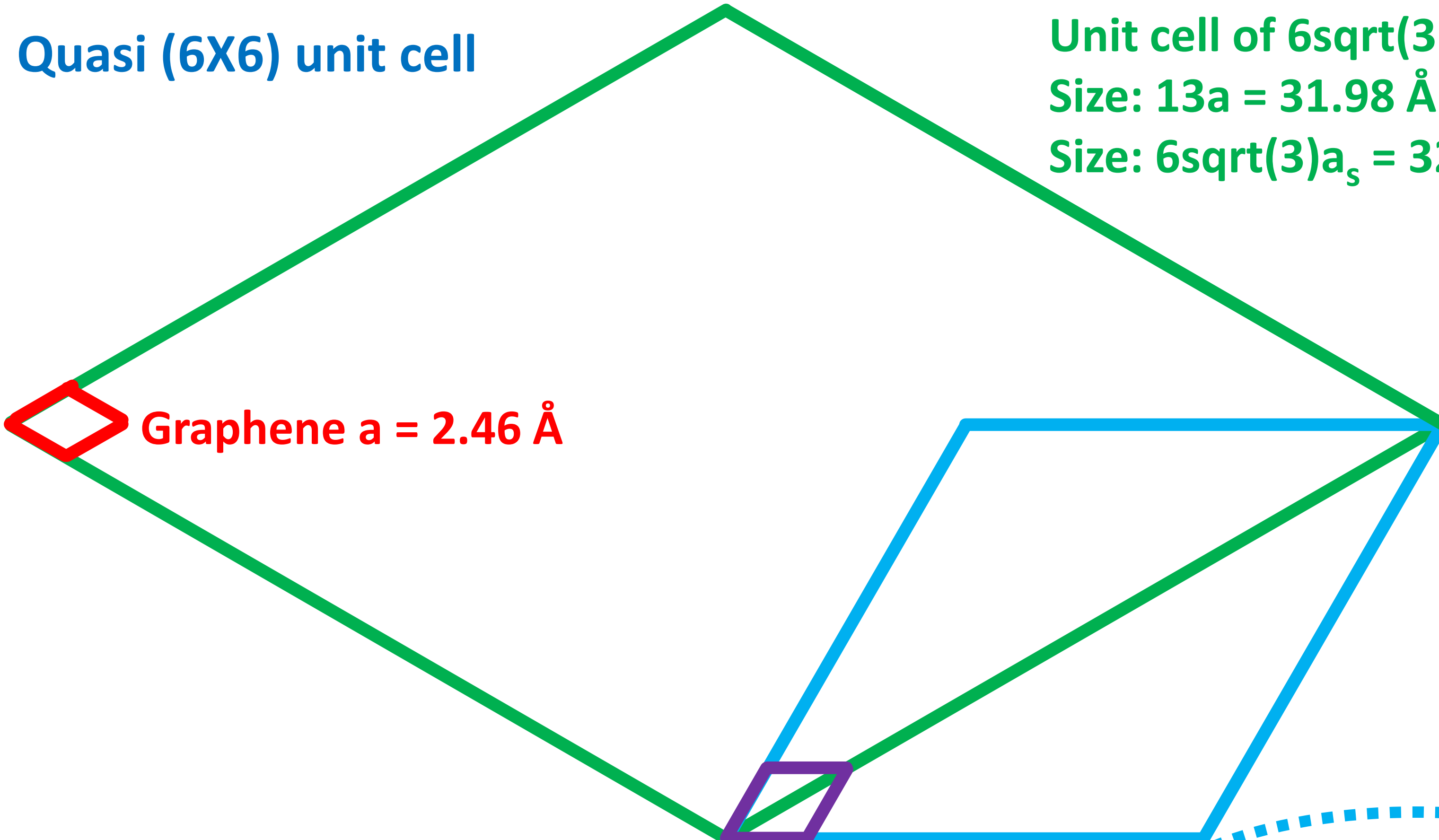


Graphene on SiC(0001)
Si
C
Graphene
a_s = 3.08 Å
a = 2.46 Å

Quasi (6X6) unit cell



Measured value is 17Å (corresponds to a strain of 0.8%)
17Å is nearly exactly 4 times the InAs(111) lattice constant: a(InAs) = 6.0583Å, in the (111) plane
a(InAs) =6.0583Å/sqrt(2) = 4.284A, X 4 = 17.1Å