III-V Nanowire Growth for Quantum Photonics and Optoelectronics

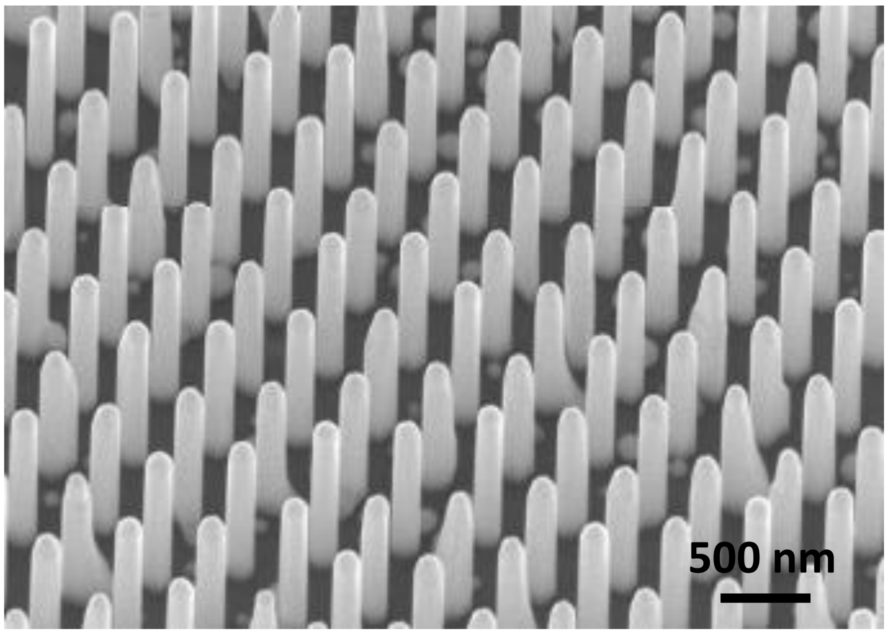
McMaster University

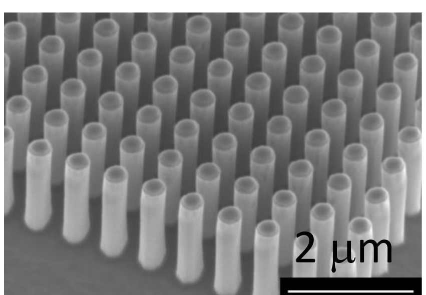
Ray LaPierre
lapierr@mcmaster.ca
Department of Engineering Physics
McMaster University, Hamilton, Ontario, Canada

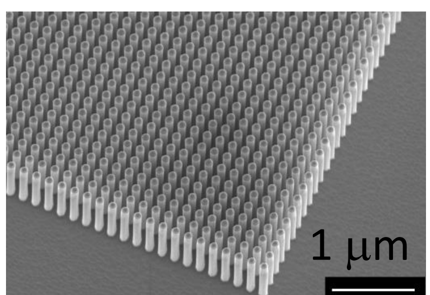
rit photonics for Quantum.2

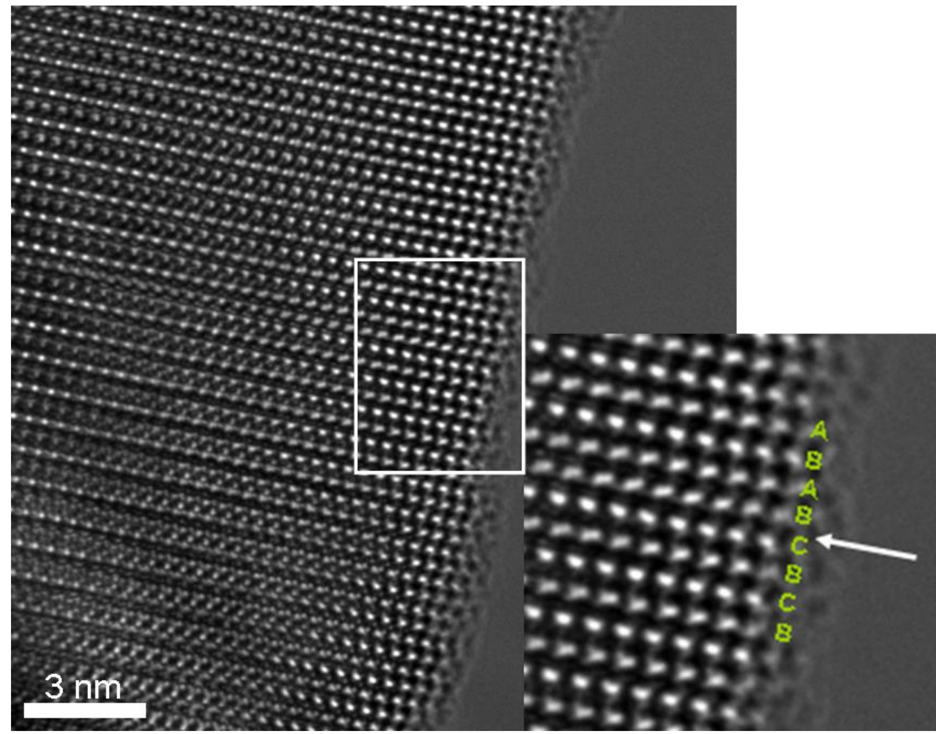
Semiconductor Nanowires

2D array of semiconductor rods
III-V material: (In,Ga,Al)-(P,As,Sb)
Single crystals
Diameter ~ 10 – 500 nm
Length ~ 1 – 10 μm





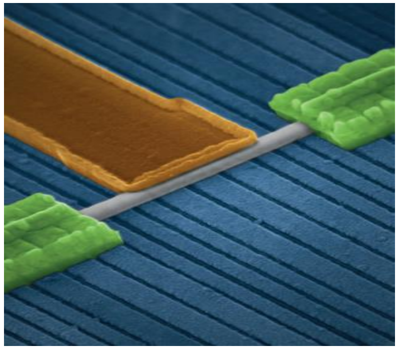




The Role of III-V Nanowires in Quantum Information Science and Engineering

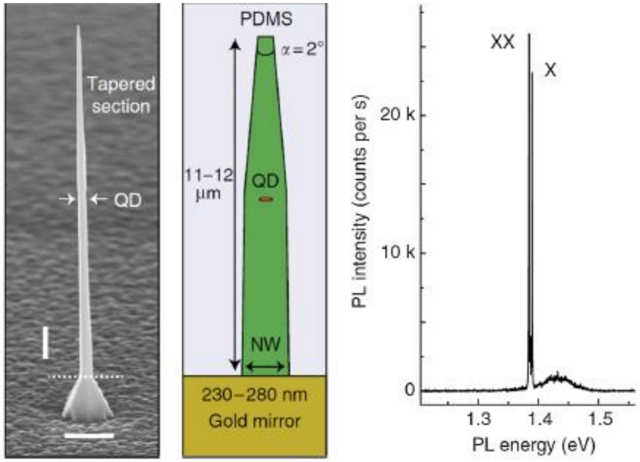
- Majorana fermions

  Science 336 (2012) 1003
  Nature Physics 8 (2012) 887

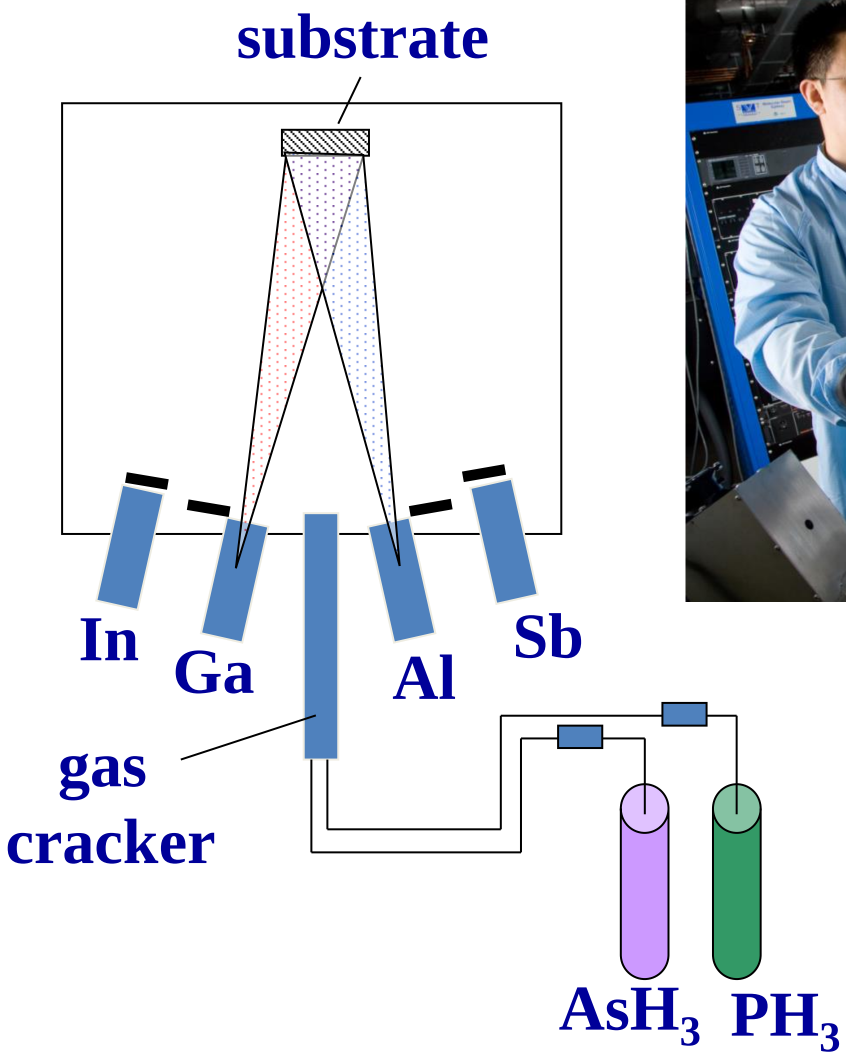


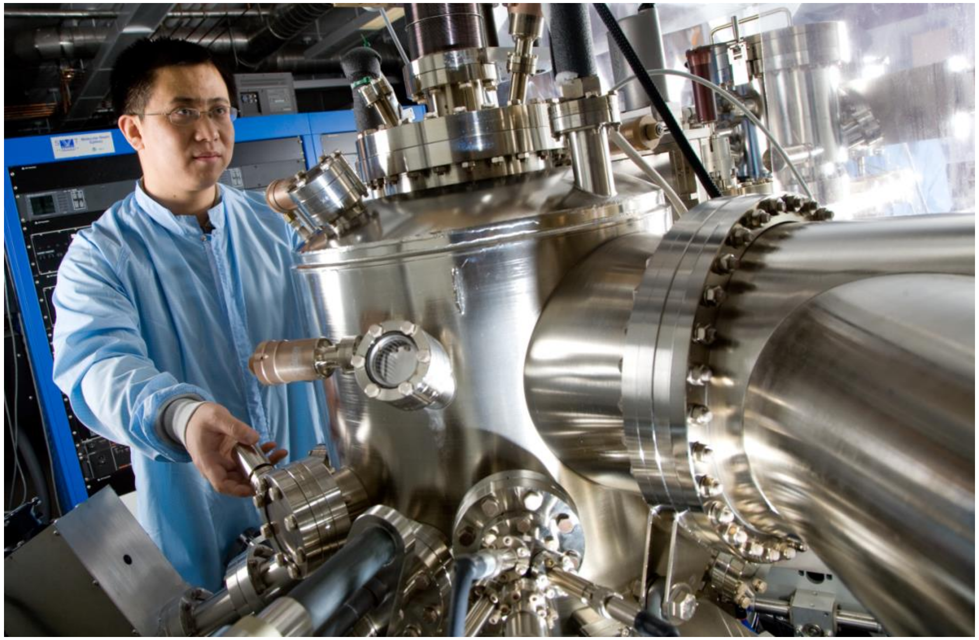
- Single photon sources & detectors

  Nat. Commun. 3 (2012) 737
  Nat. Nanotech. 12 (2017) 1026
  QIP (2020) 19, 44
  Materials (2020) 13, 1400



Molecular Beam Epitaxy (MBE)



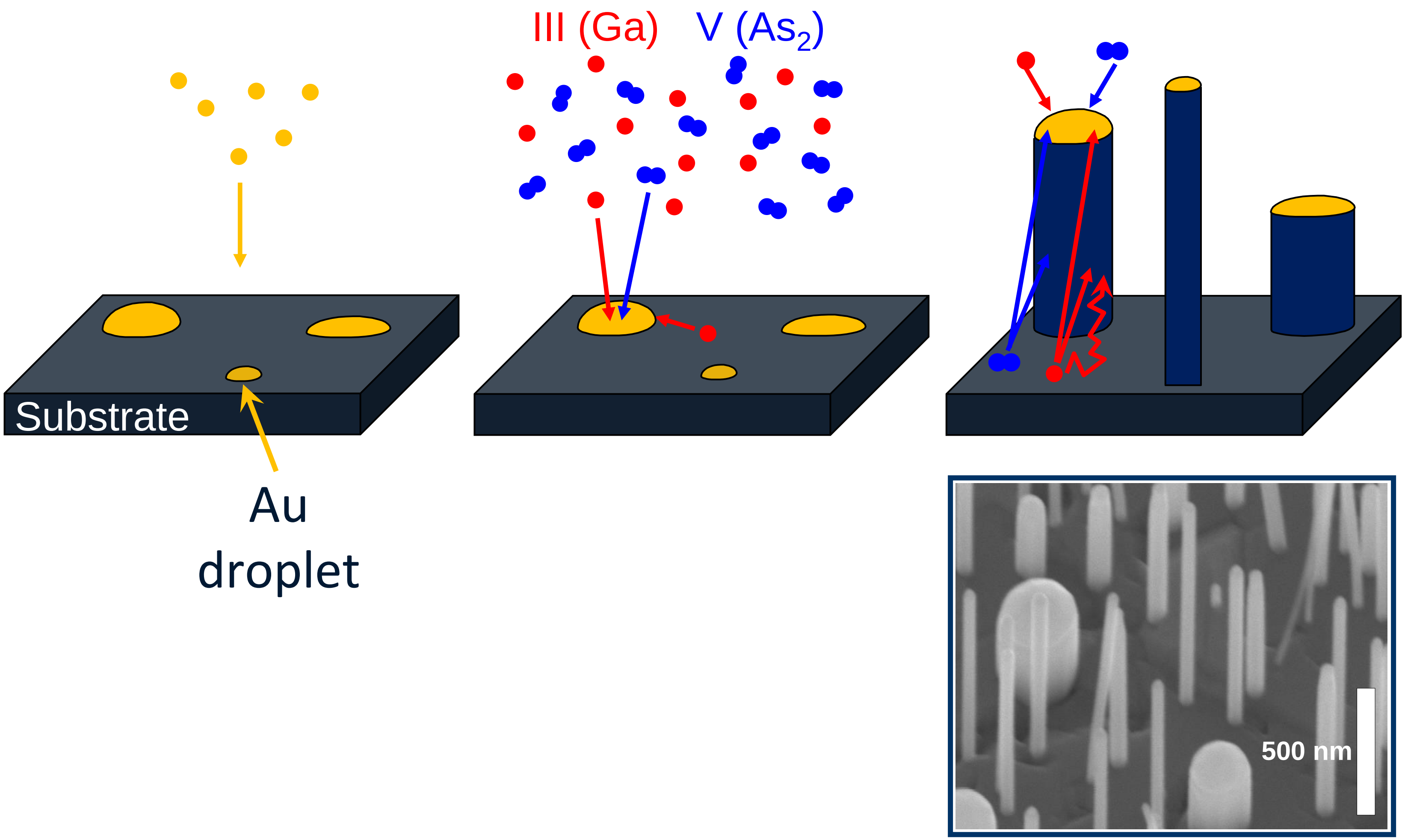


Au-assisted Nanowire Growth Process

Au deposition

III-V deposition (MBE)

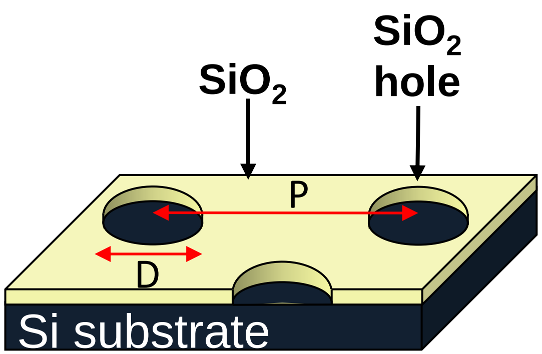
Diameter & length dispersion

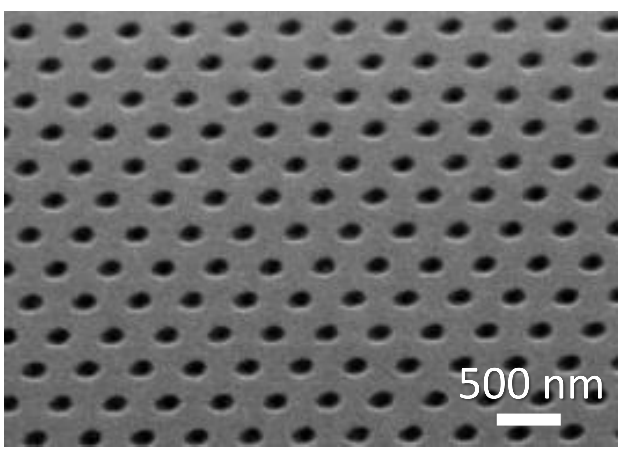


Self-assisted Selective-area Epitaxy

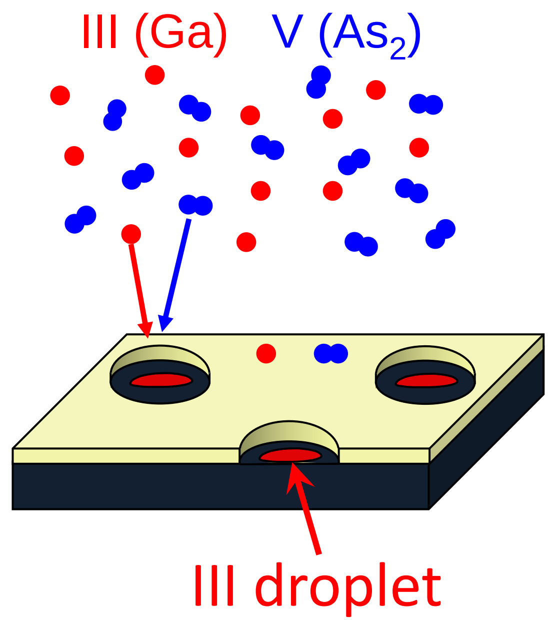
Lithographic patterning

D = 50-100 nm
P = 360 – 1000 nm

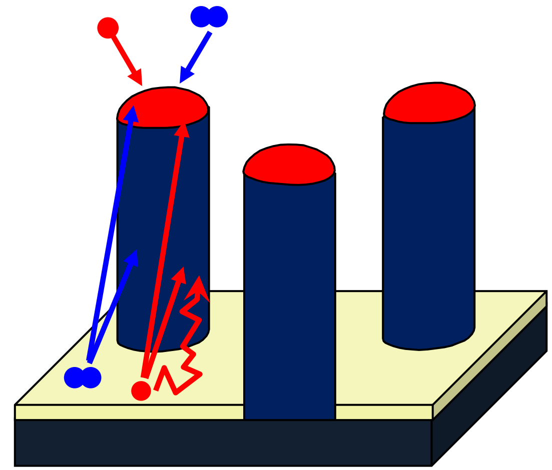


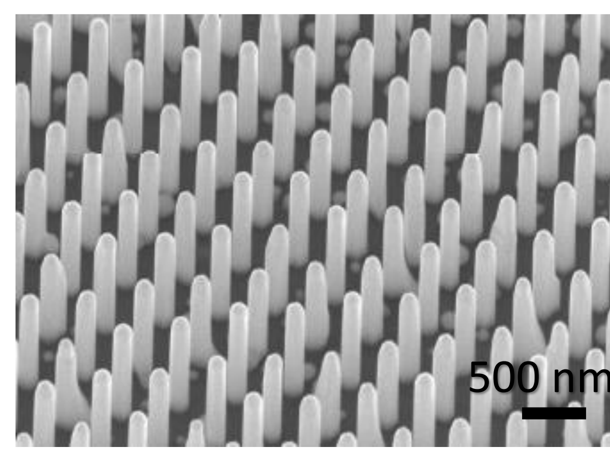


III-V deposition (MBE)

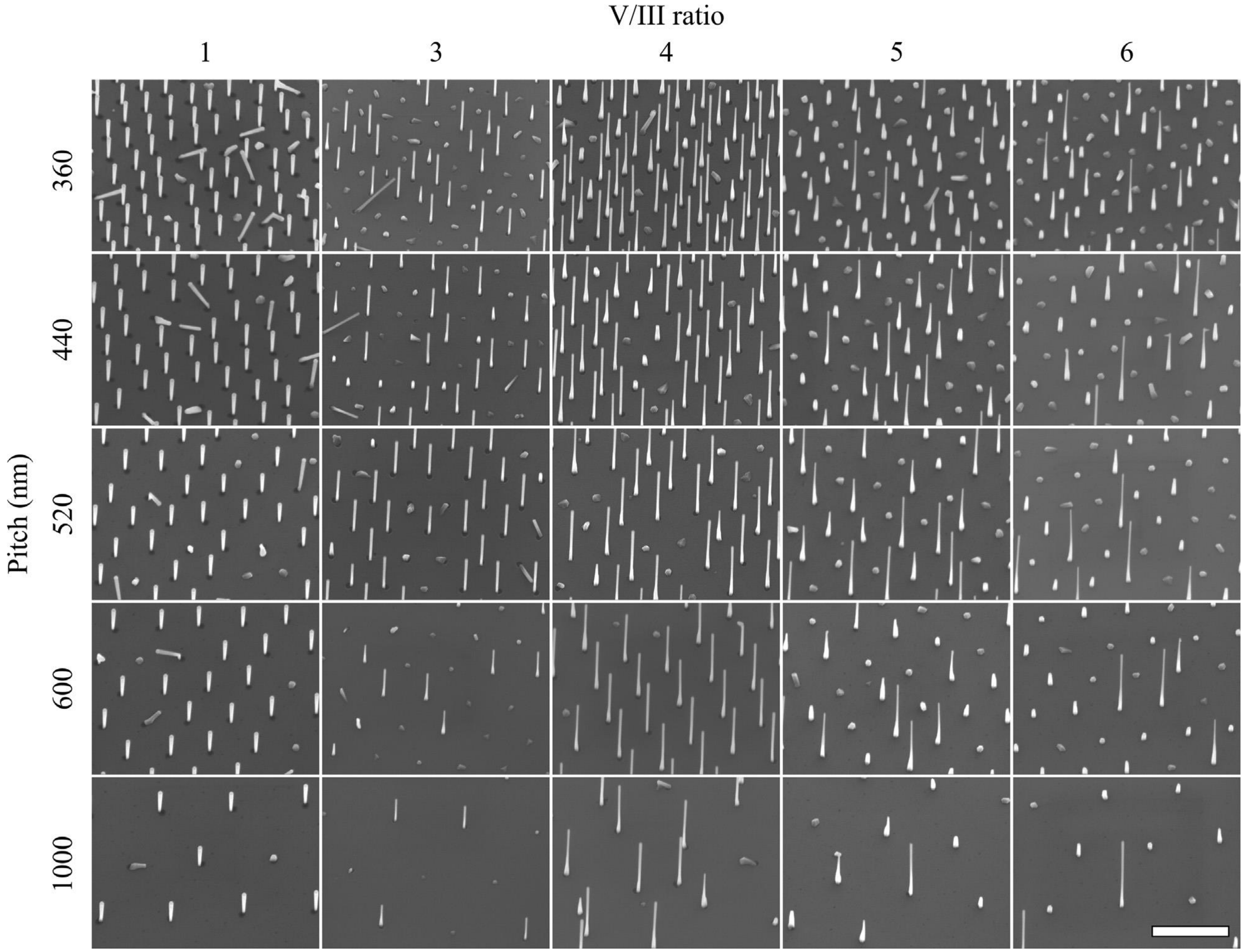


Controlled length, diameter, position, composition & doping





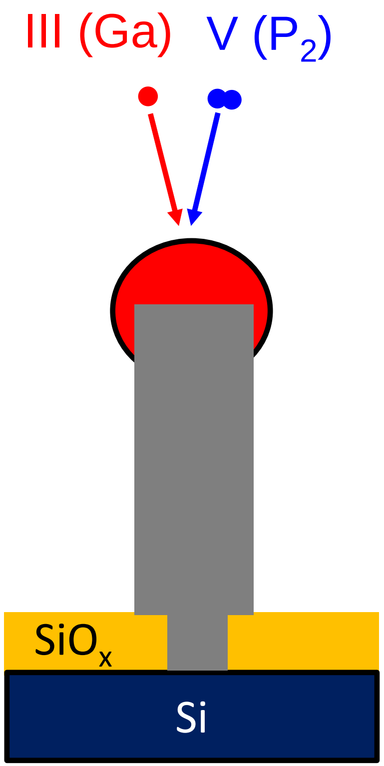
Example: GaP Nanowires

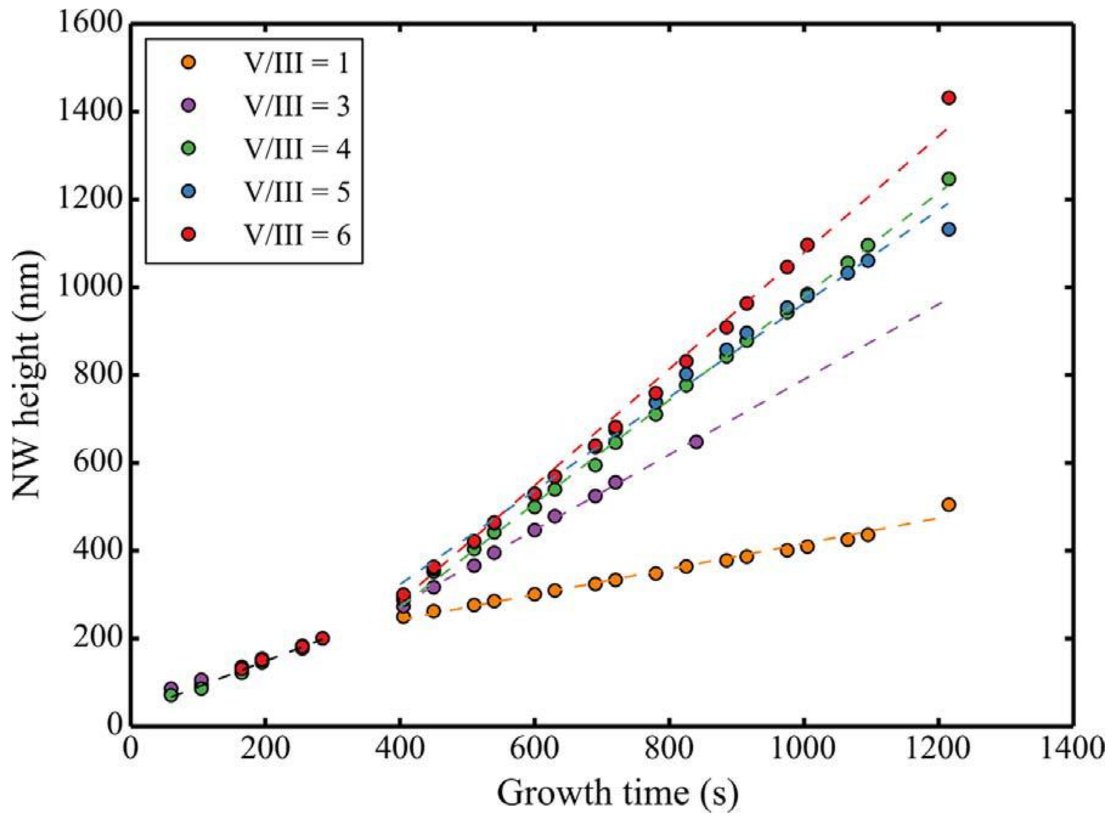


J. Crystal Growth 462 (2017) 29

Group V Dependence

Primary Flux

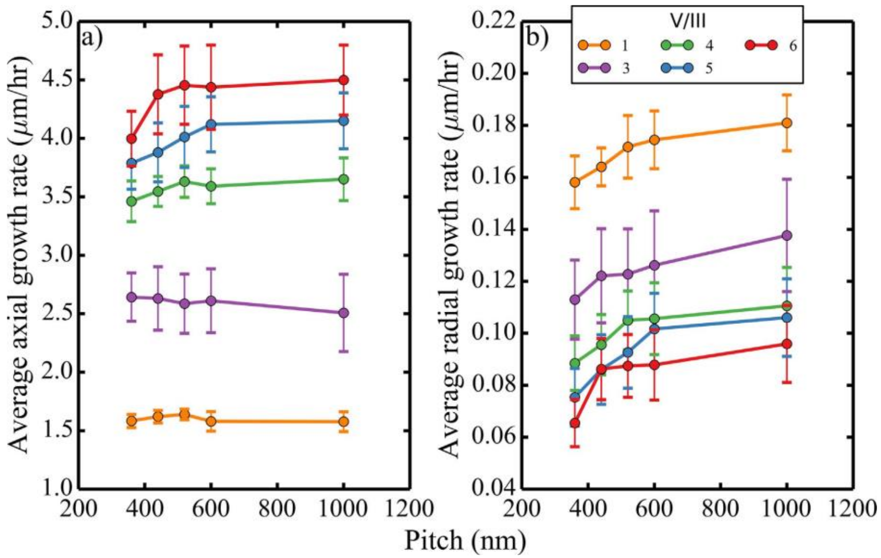




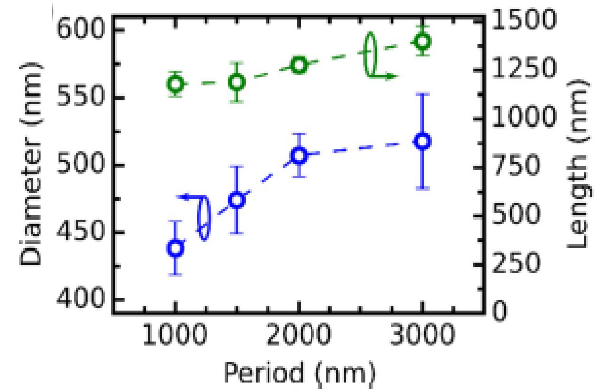
J. Crystal Growth 462 (2017) 29

Pitch/Period Dependence

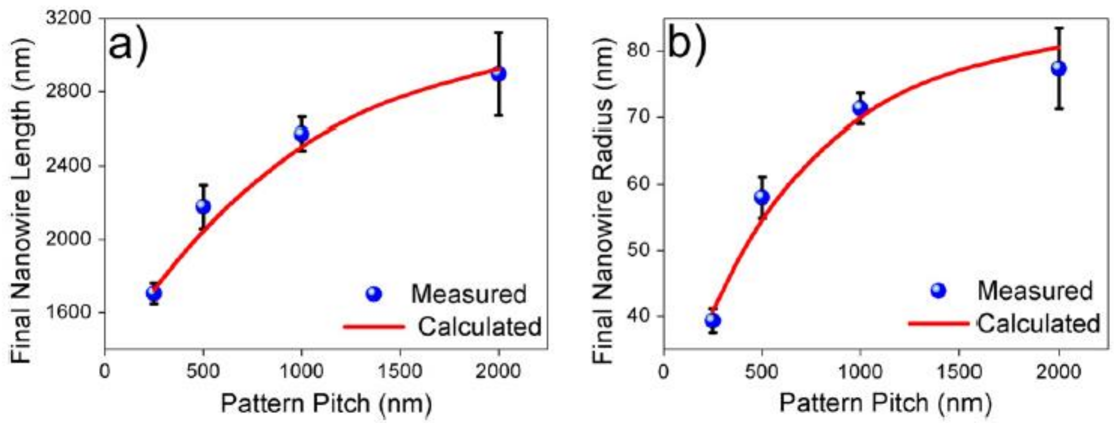
GaP



InSb



GaAs

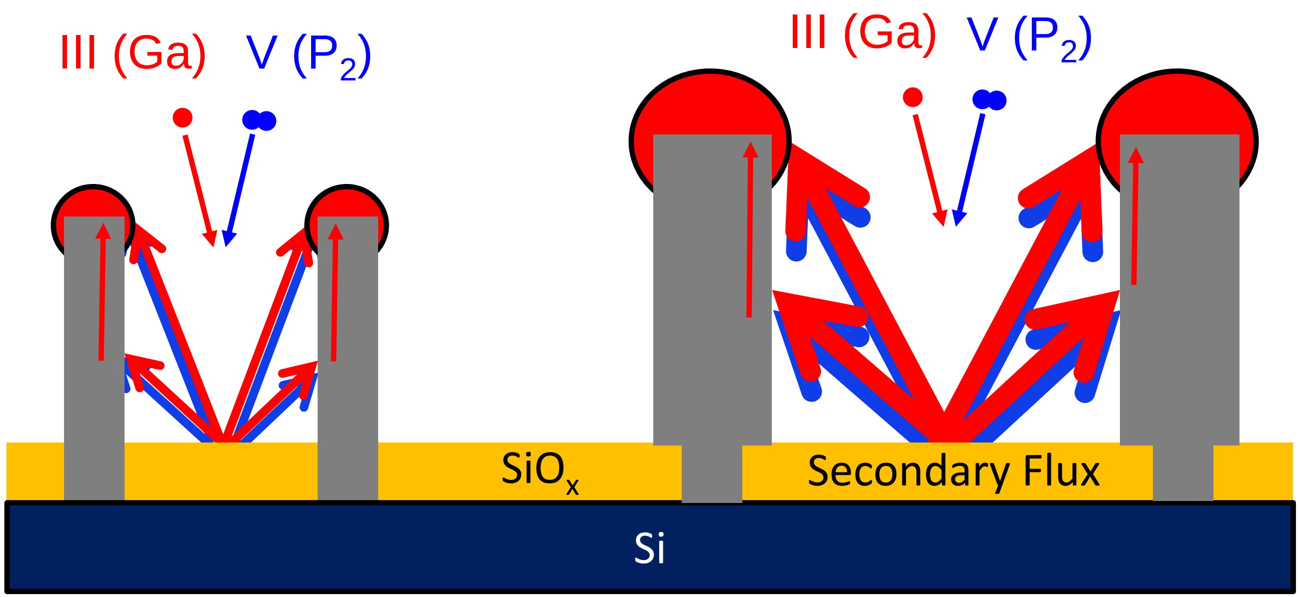


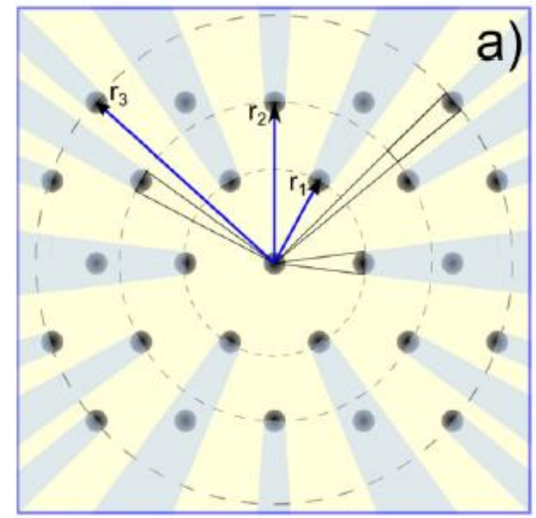
J. Crystal Growth 462 (2017) 29

Nanotechnology 25 (2014) 415304

Nano Futures 1 (2017) 035001

Pitch Dependence

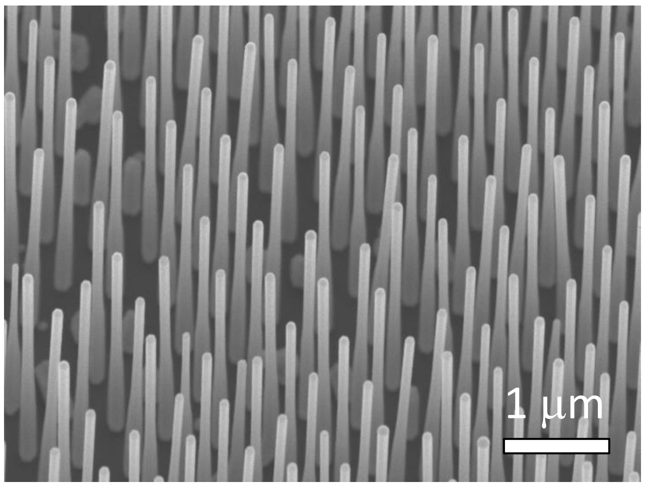




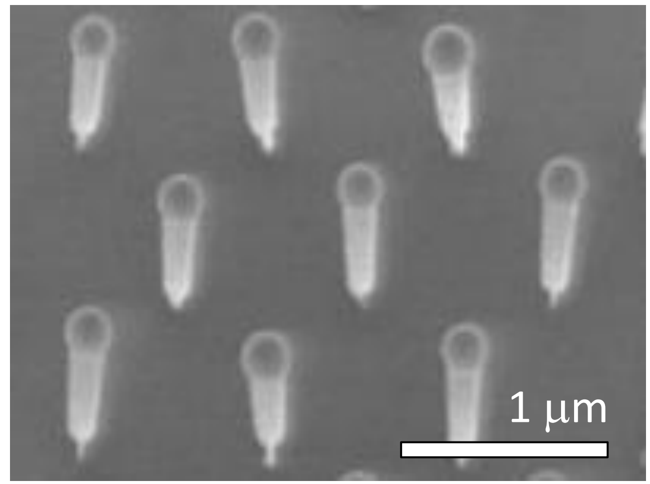
Nanotechnology 25 (2014) 415304

Droplet Dynamics: Diameter Control

V/III flux ratio > 1



V/III flux ratio ~ 1

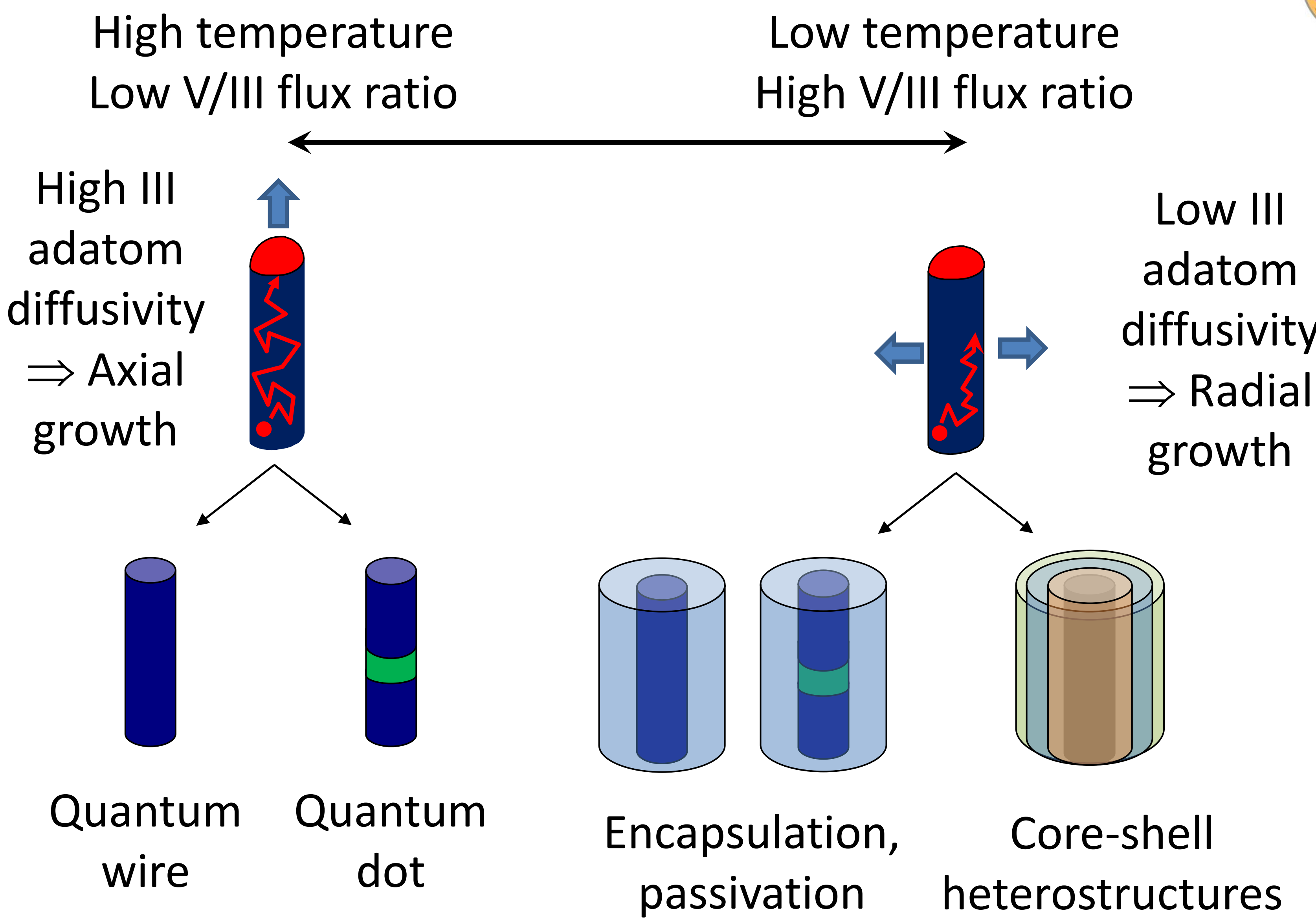


Optical funnel/horn

IEEE J. Photovolt. 9 (2019) 1225

Group III Dependence

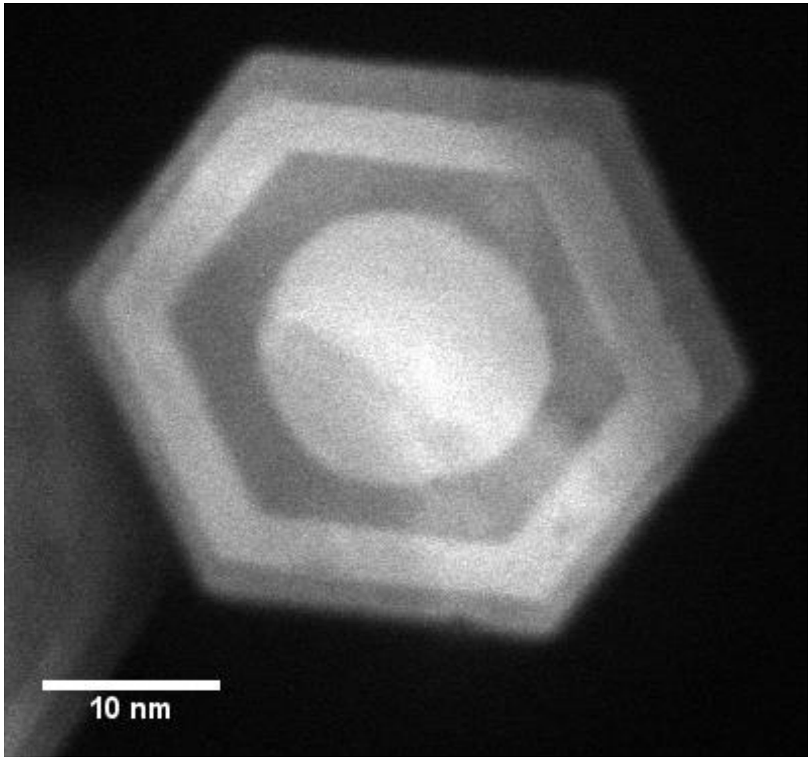
McMaster University

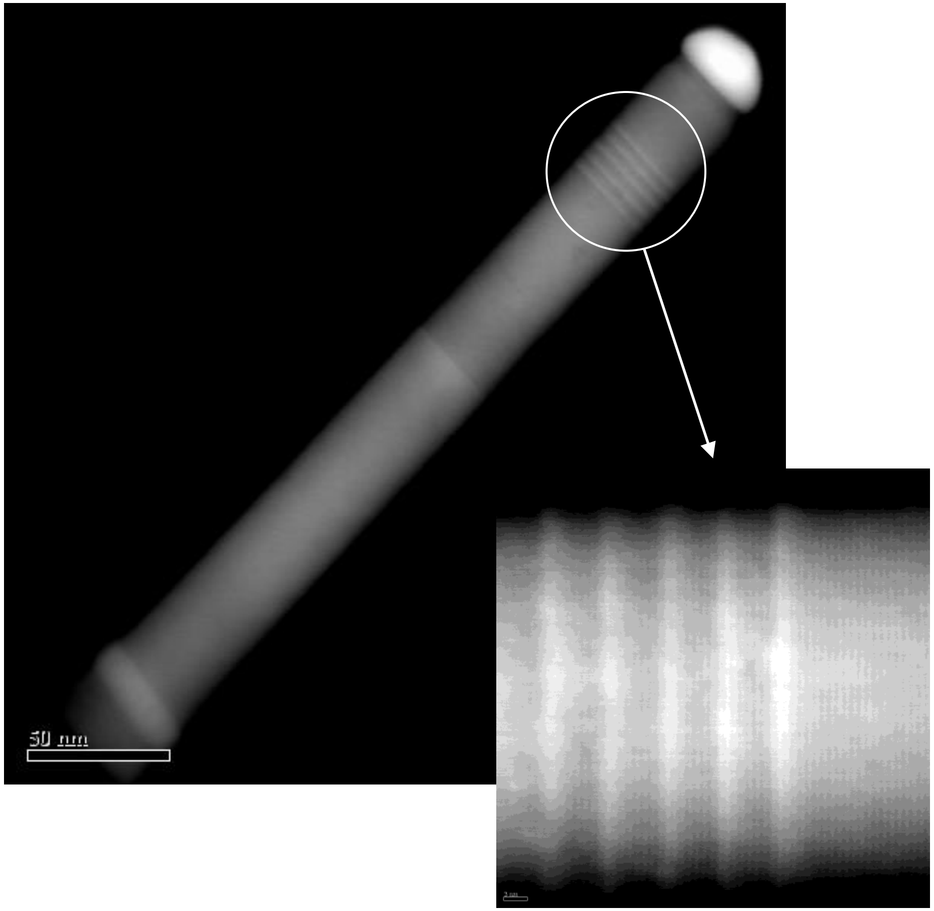


Opportunity 1: Unique Heterostructures

Core-Shell Heterostructures
- Radial quantum wells

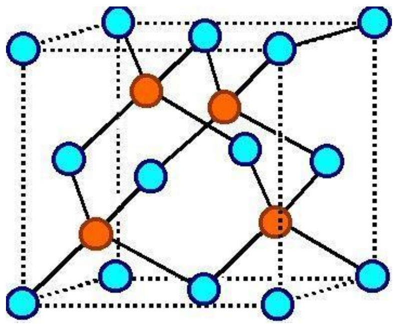
Axial Heterostructures
- Quantum dots
- Superlattices



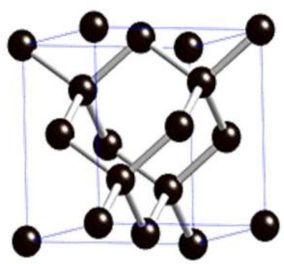


Opportunity 2: Heterogeneous Growth on Si

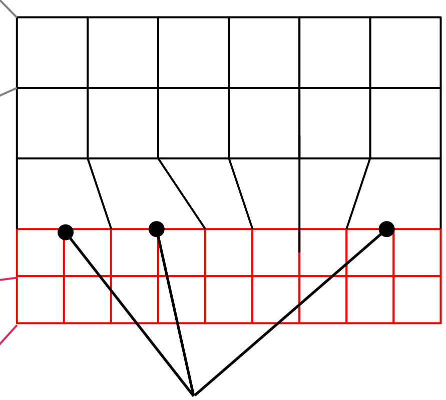
III-V
zinc-blende
crystal
structure



Si
diamond
crystal
structure



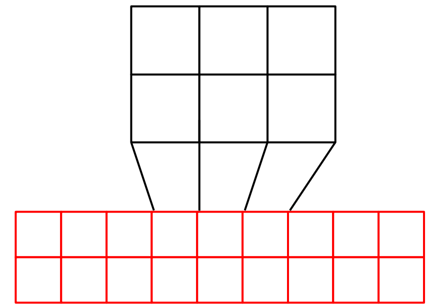
Thin Films



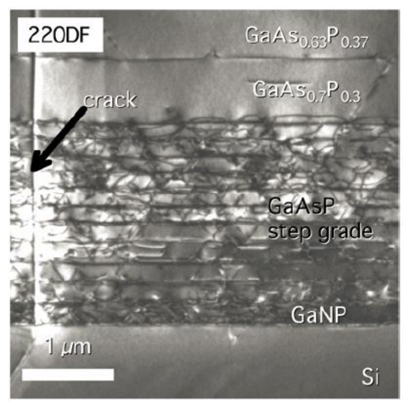
Nanowires

III-V

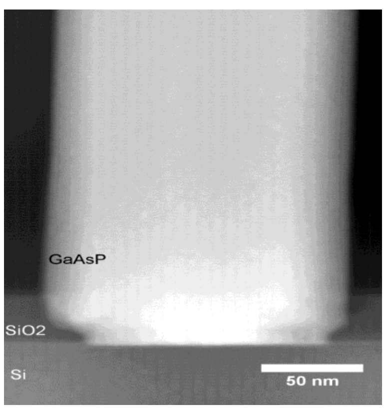
Si

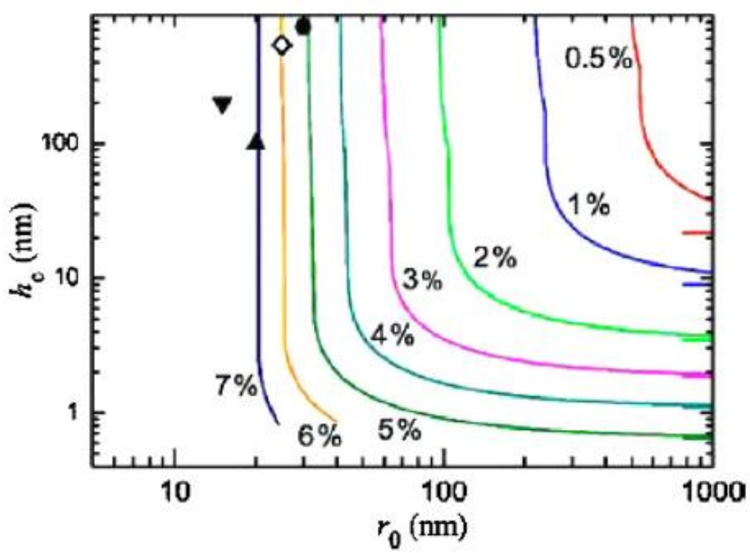


Dislocations



Dislocation-free

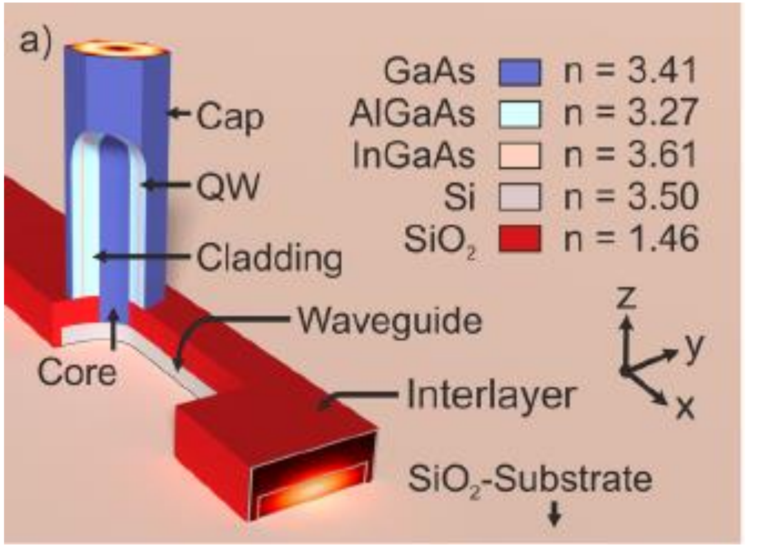




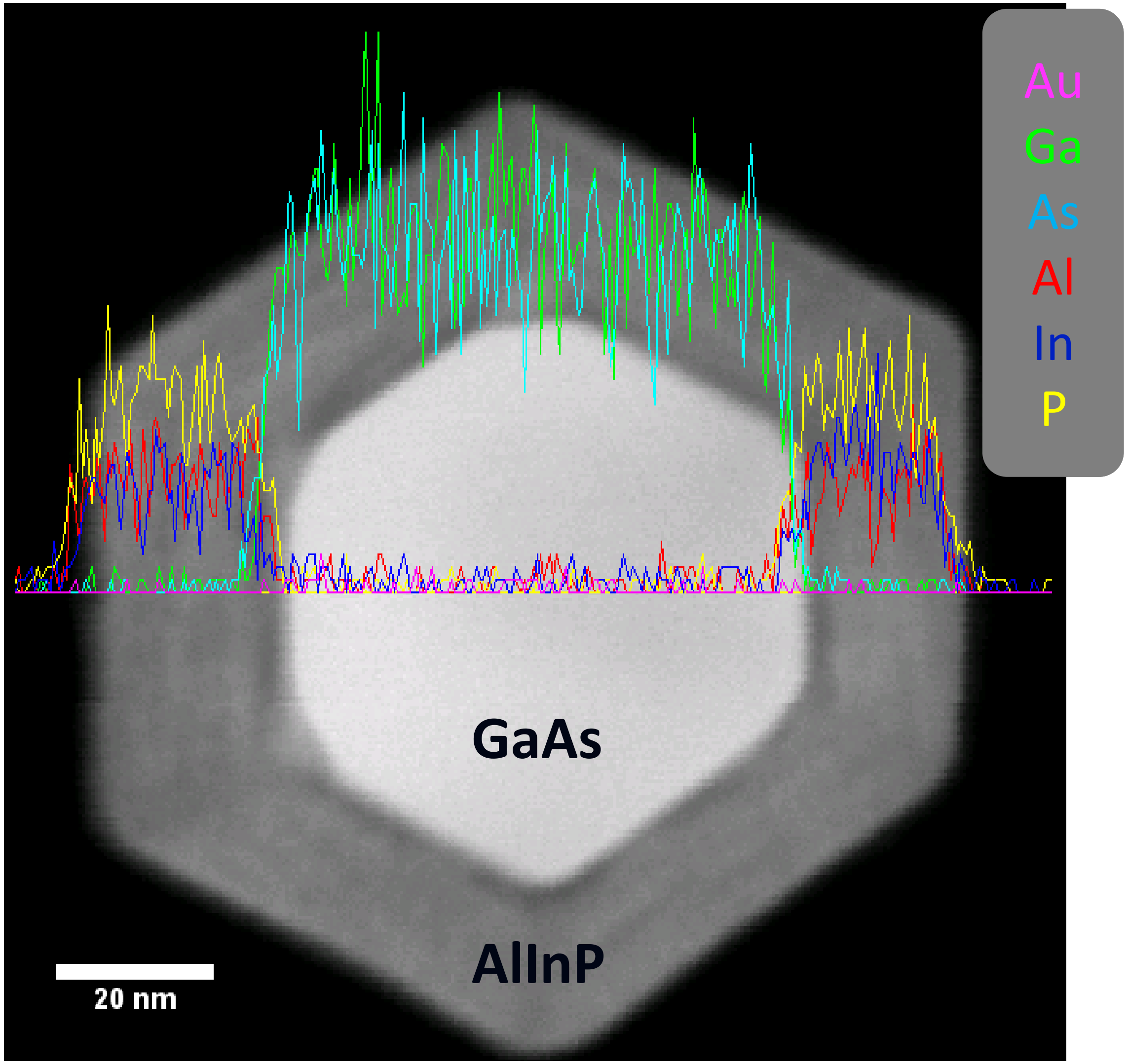
PRB 74 (2006) 121302(R)

Integration with Si Photonics

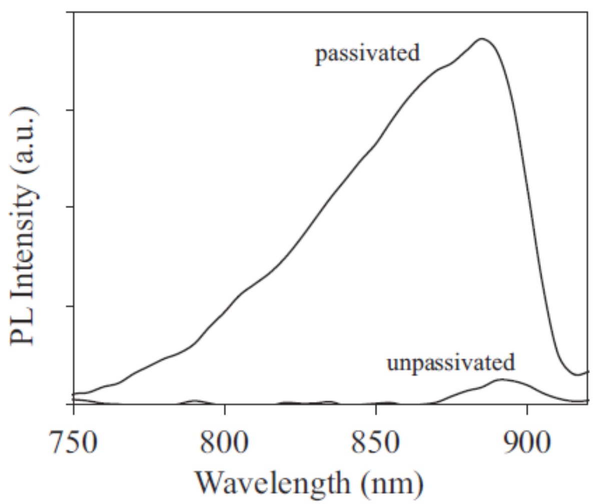
ACS Photonics 7 (2020) 1016
J. Appl. Phys. 125 (2019) 243102
Appl. Phys. Lett. 115 (2019) 213101
PSS RRL 13 (2019) 1800489
Nano Lett. 17 (2017) 5244
Nano Lett. 16 (2016) 1833
ACS Photonics 4 (2017) 2537

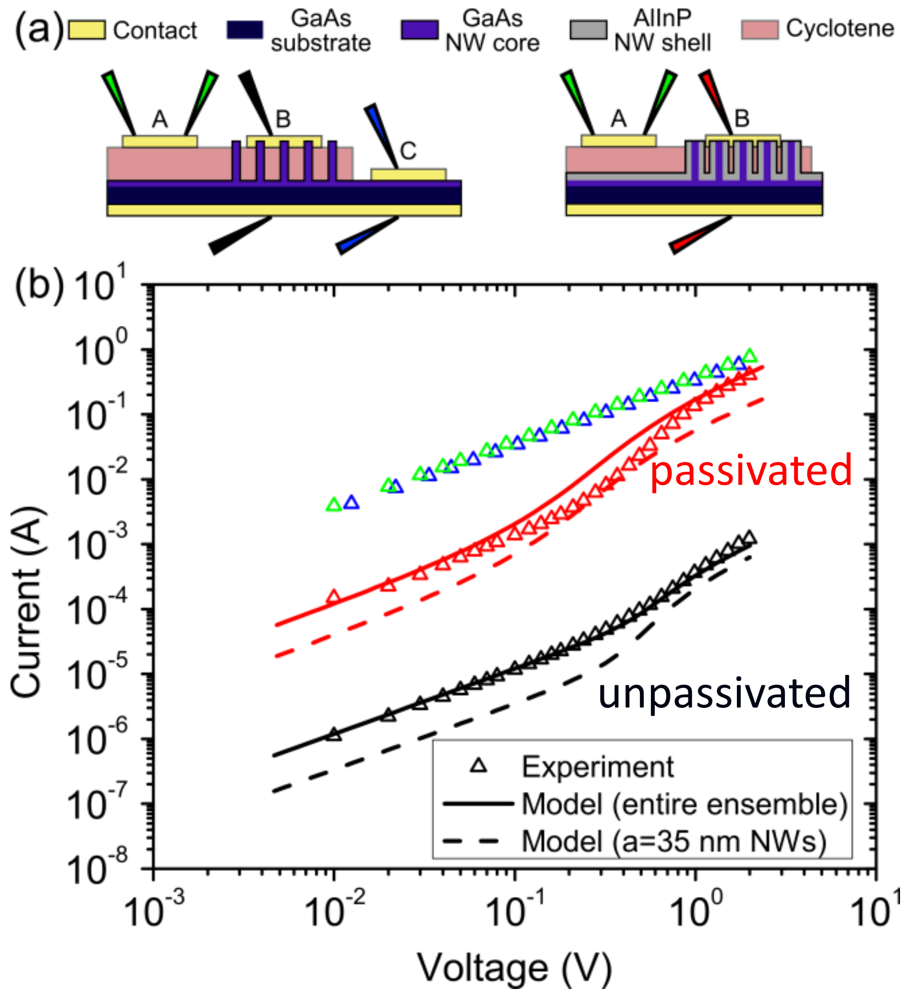


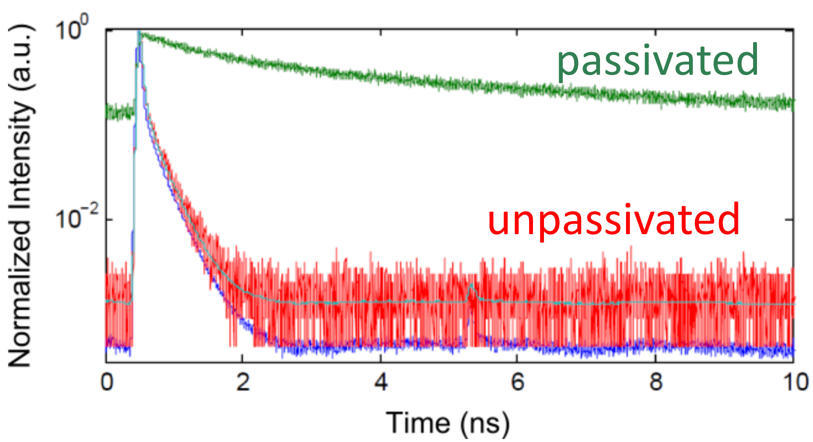
Challenge 1: Surface Passivation



Surface Passivation



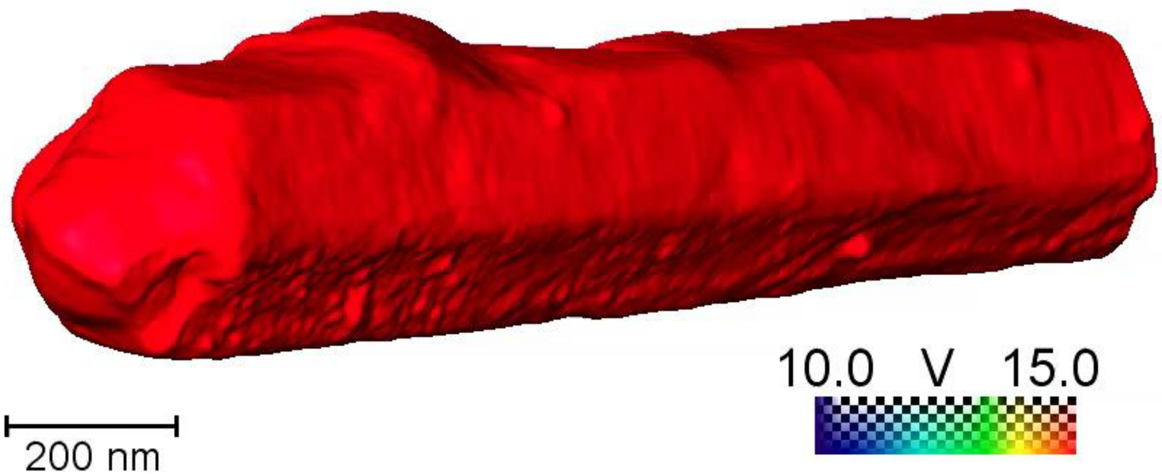




JAP 111 (2012) 094319
JAP 112 (2012) 063705
SST 28 (2013) 105026

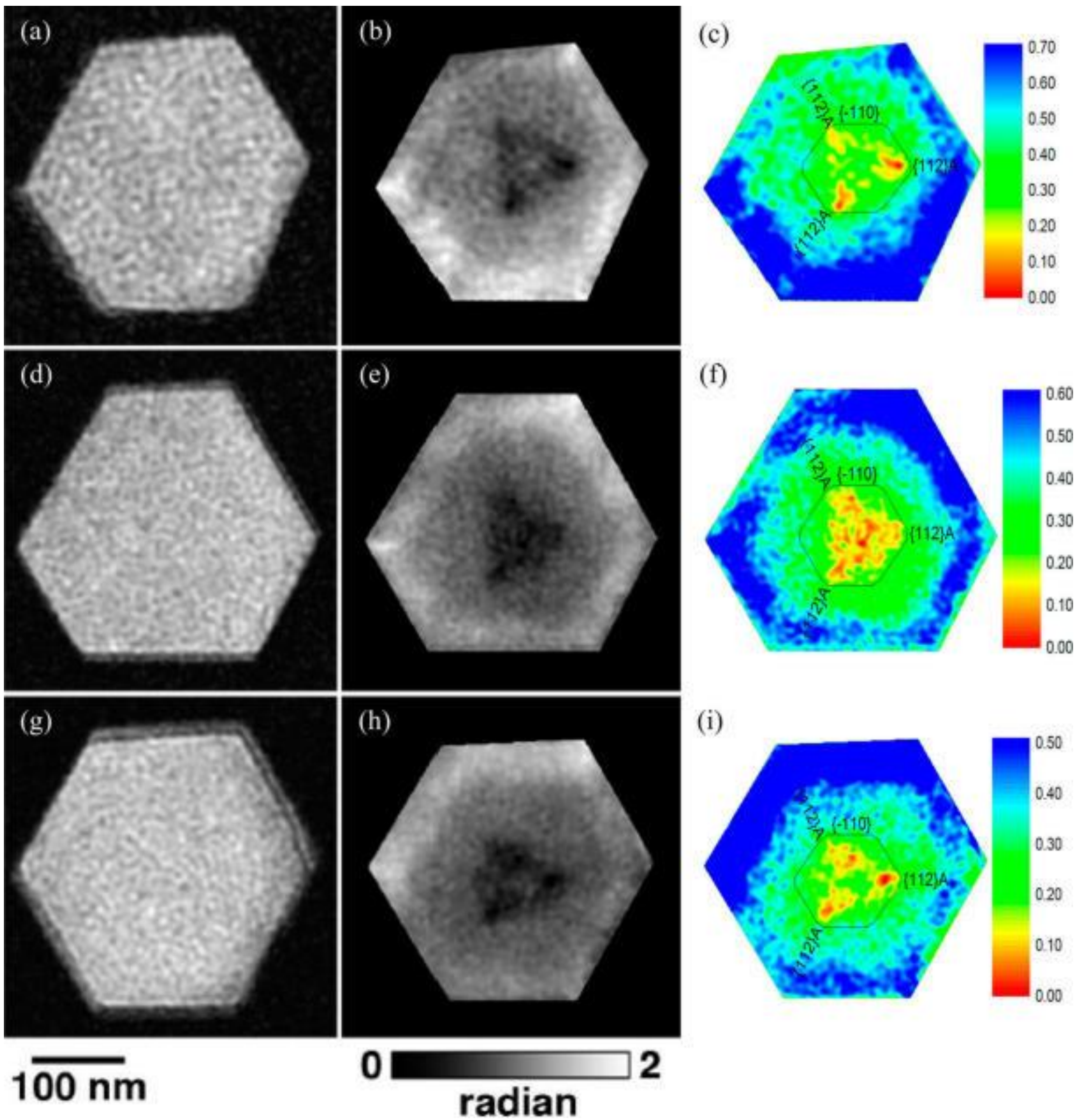
Challenge 2: Doping

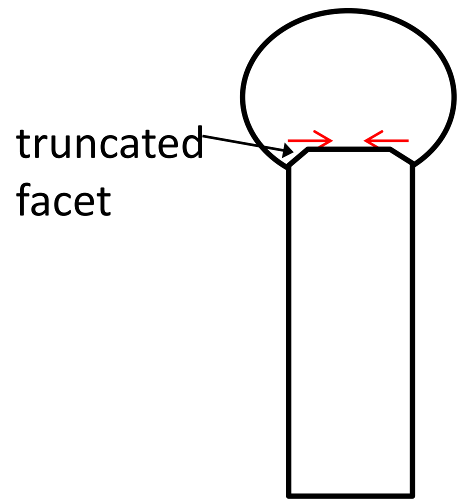
Nanowire reconstruction by electron holography



Three-fold Symmetric Doping Mechanism

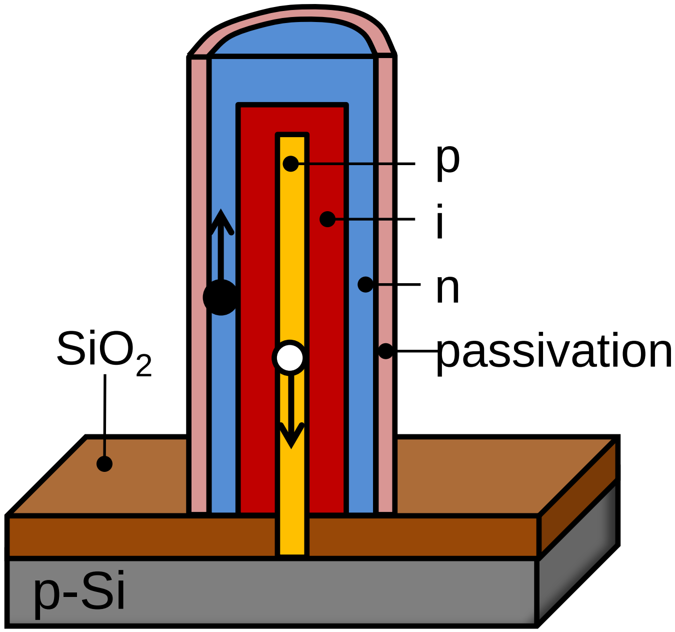
TEM | Electron holography Phase map | Built-in potential

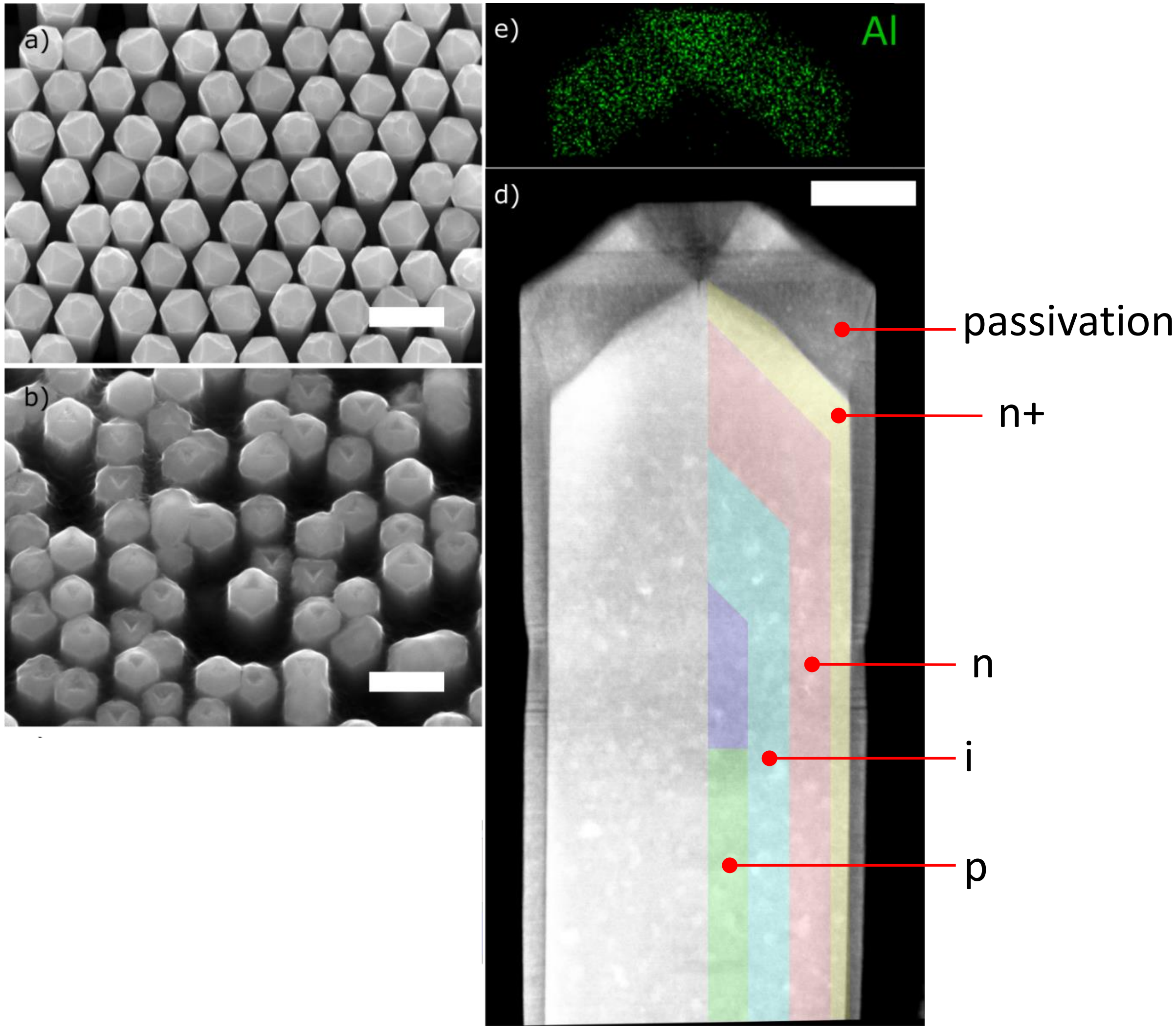




Nano Lett. 17 (2017) 5875

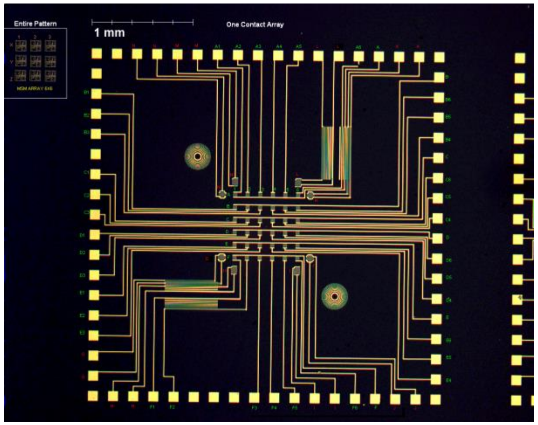
Putting It All Together: Nanowire p-i-n Structures

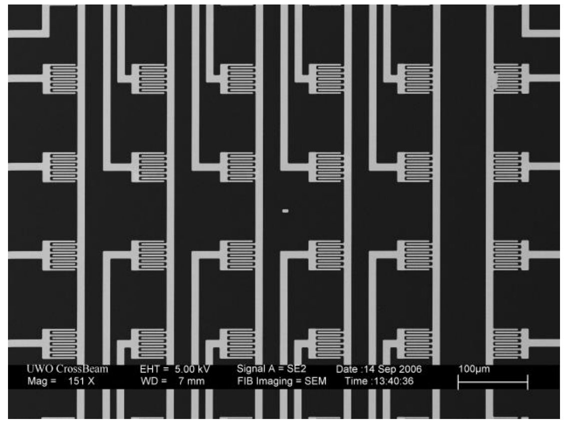


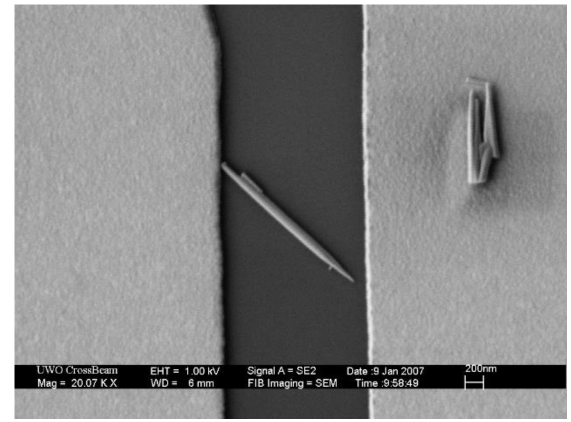


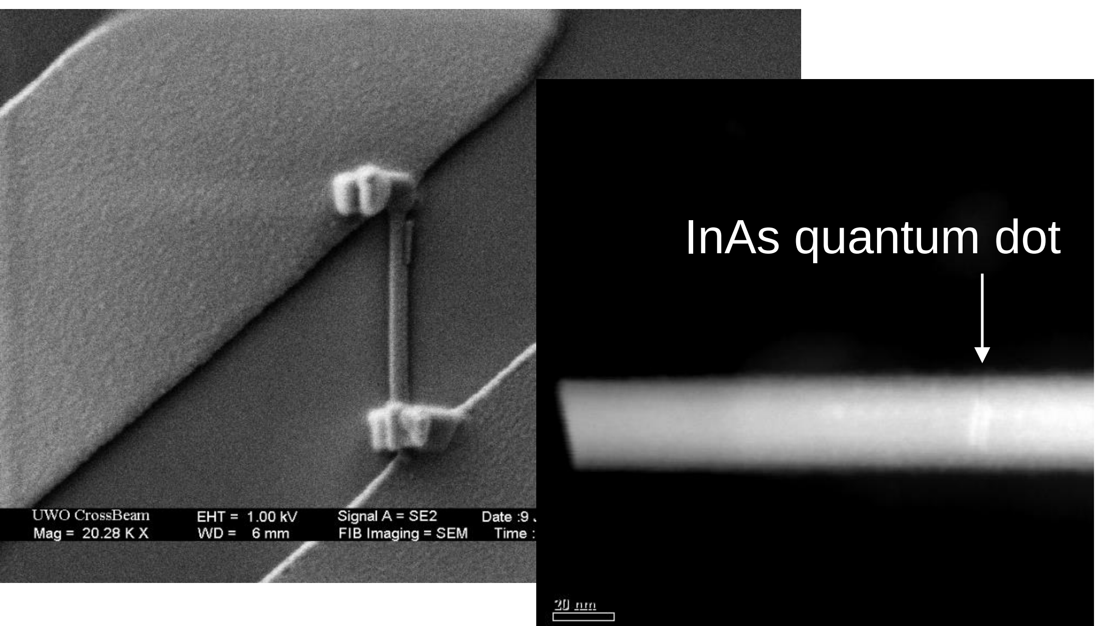
Physica Status Solidi RRL 7 (2013) 815
IEEE J. Photovoltaics 6 (2016) 661

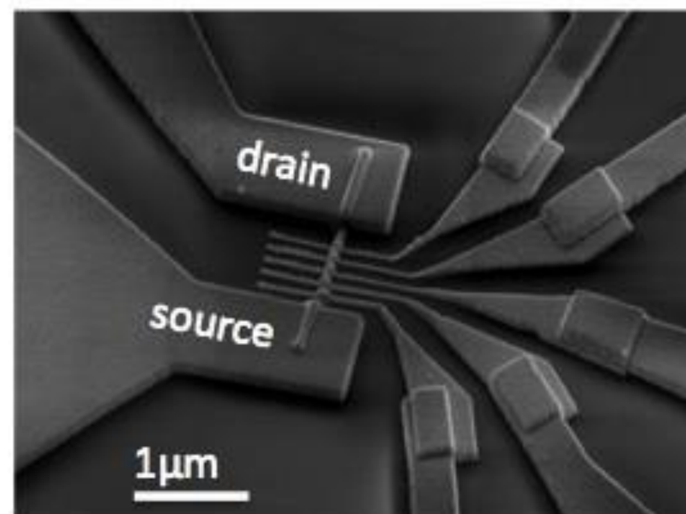
Single Nanowire Device Fabrication



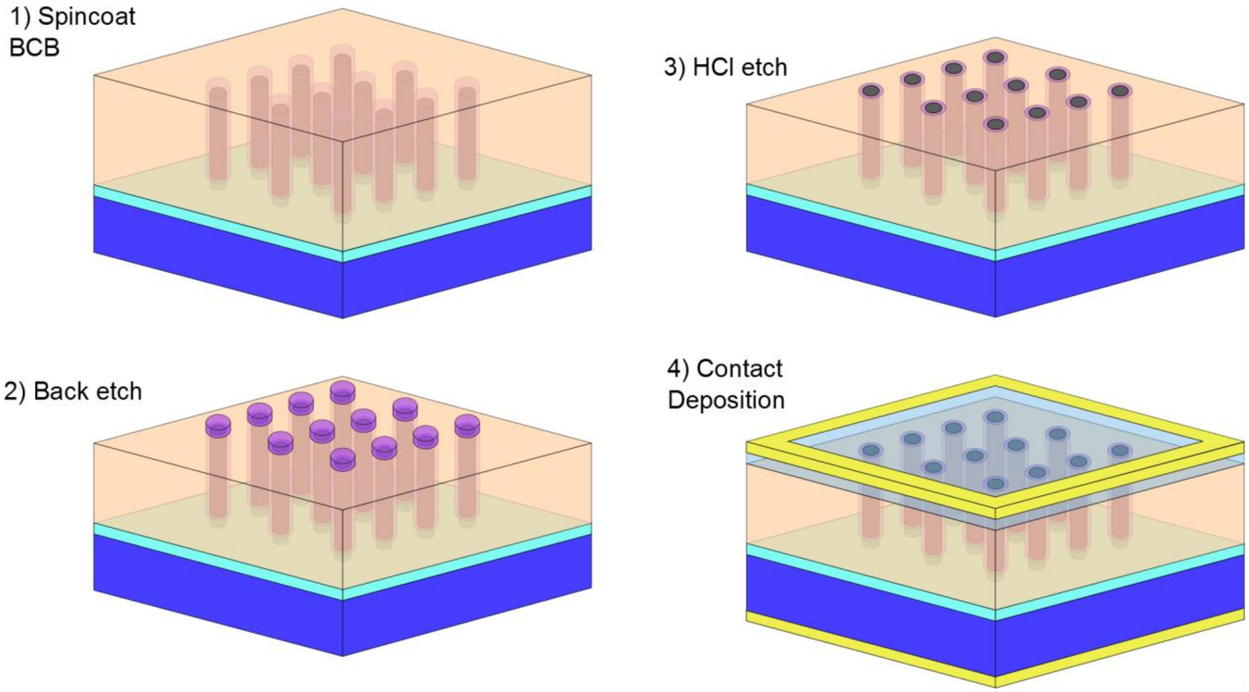


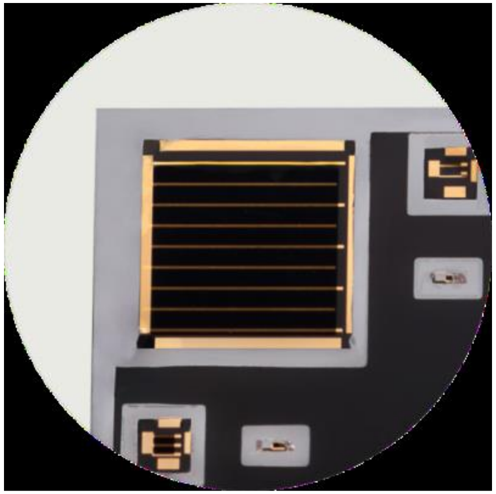




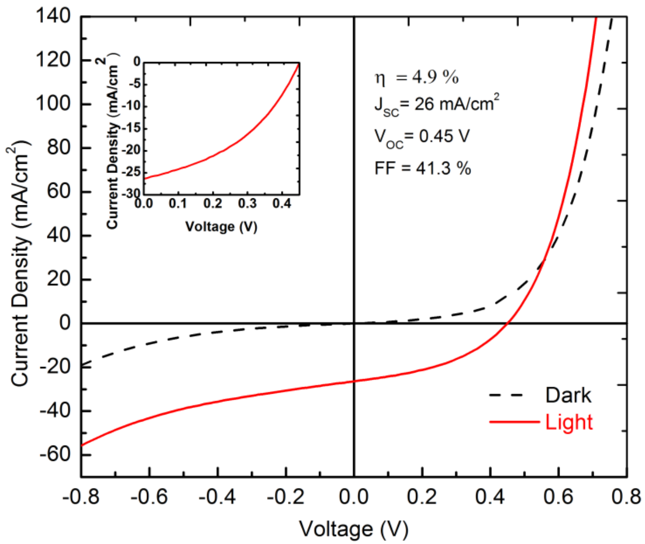


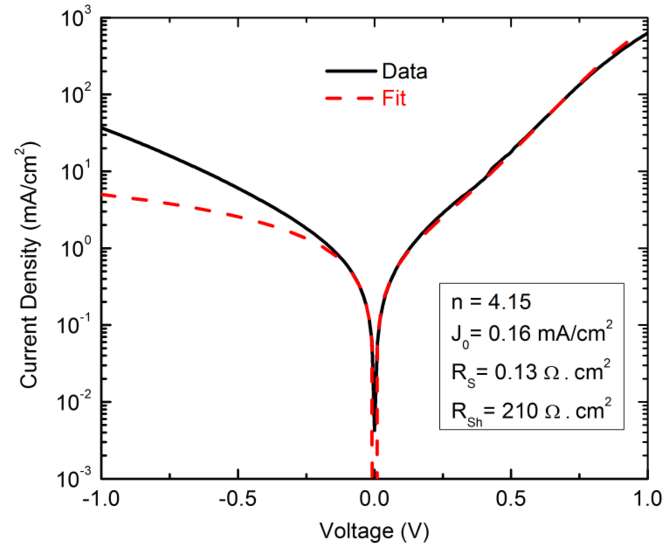
Ensemble Nanowire Device Fabrication

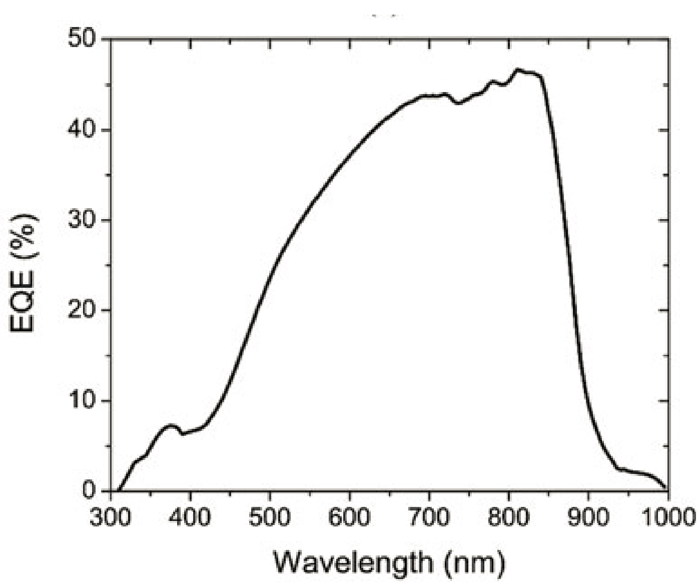


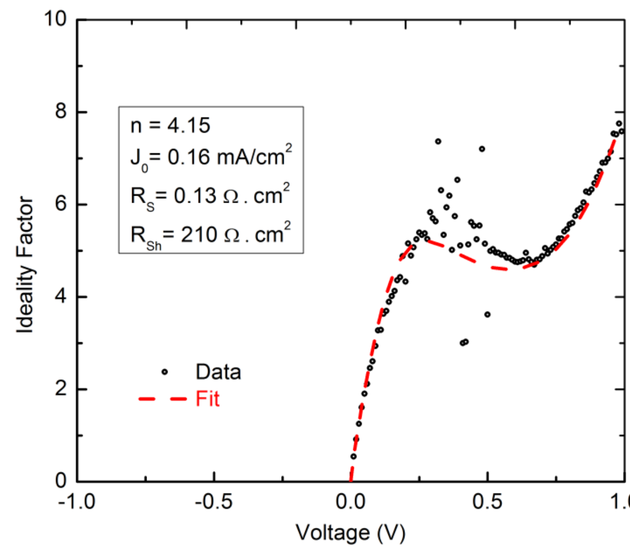


Diode Characteristics



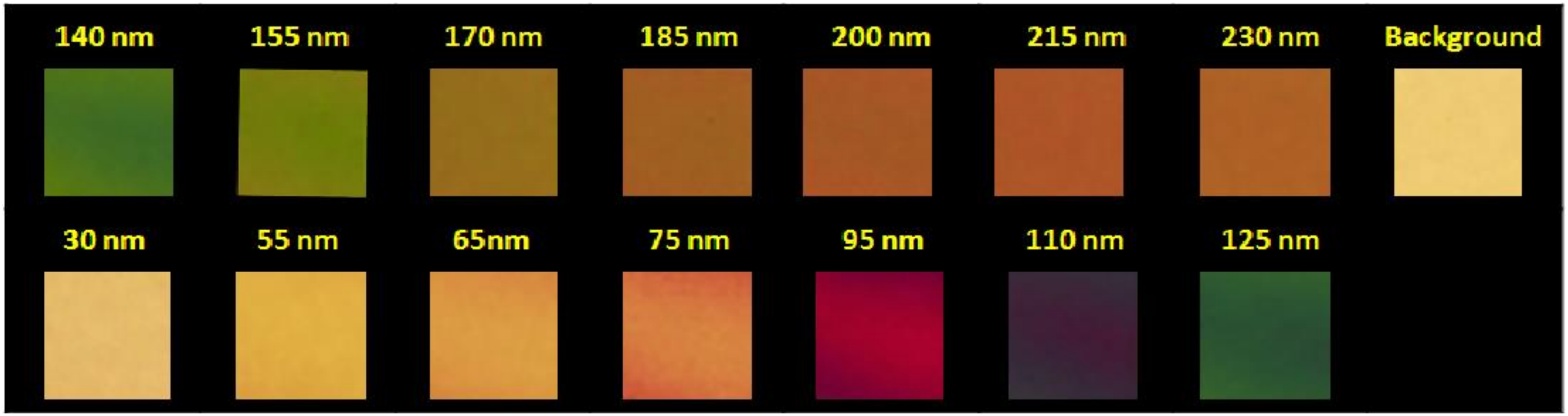


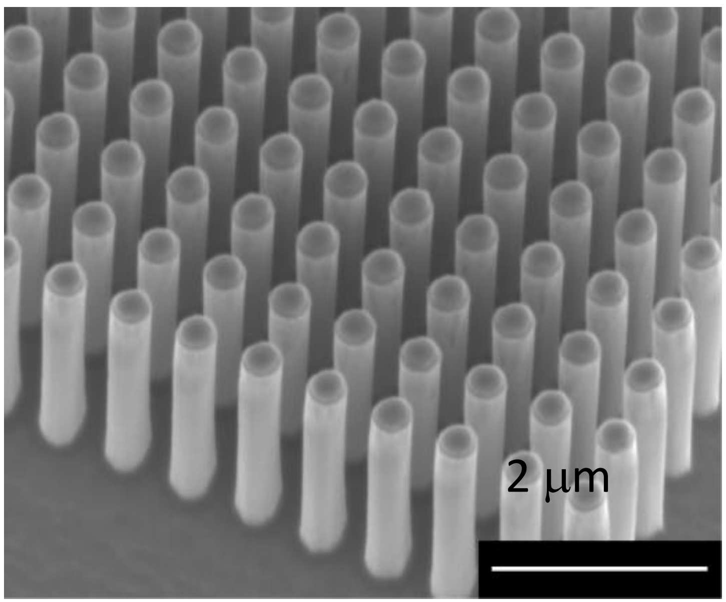




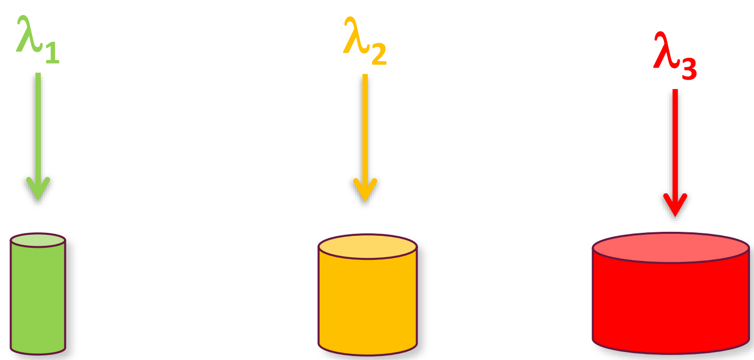
IEEE J. Photovoltaics 6 (2016) 661

Opportunity 3: Diameter-dependent Optical Absorption





Absorbed wavelength depends on nanowire diameter

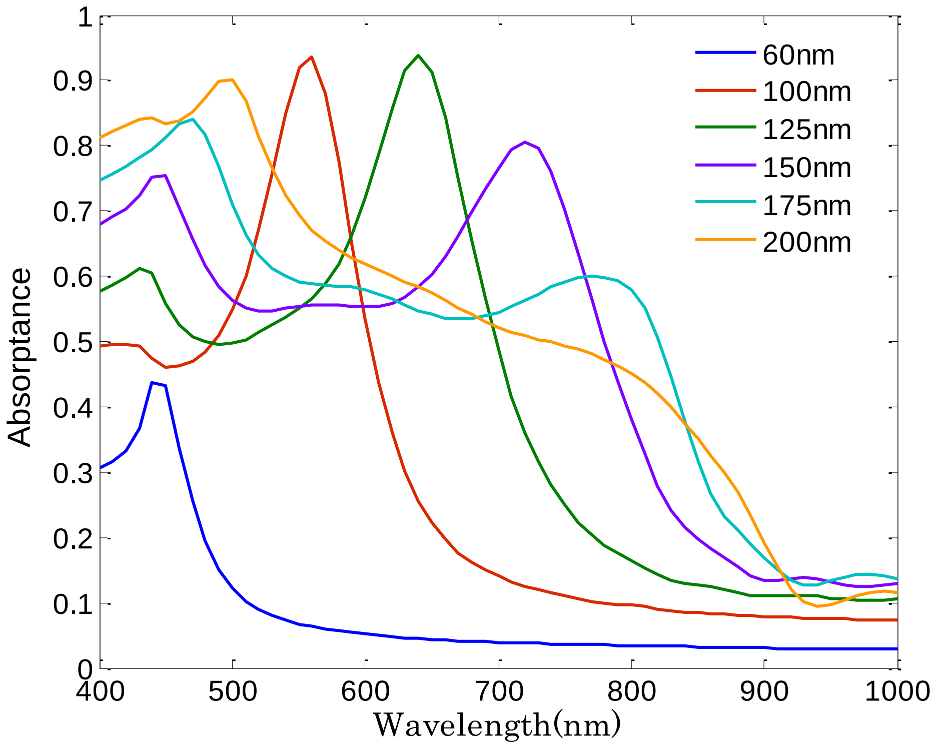


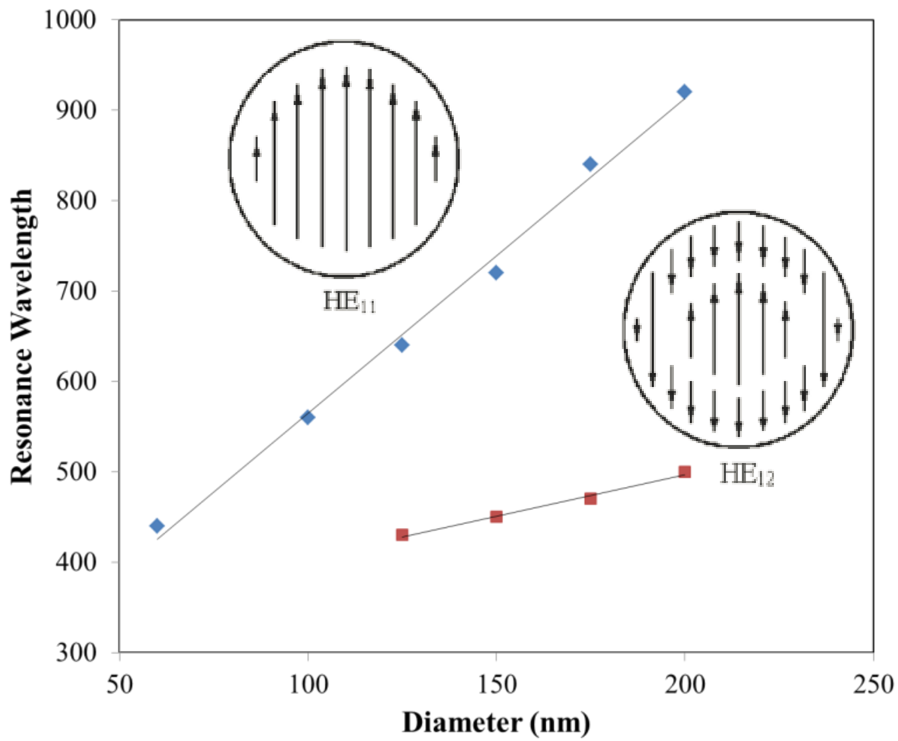
Nanotechnology 25 (2014) 305303

Nanowire Optical Resonant Modes

- HE_{1n} radial waveguide modes
- Increasing nanowire diameter $\rightarrow$ Red-shift of absorptance

GaAs, Period: 400 nm, Length: 450 nm



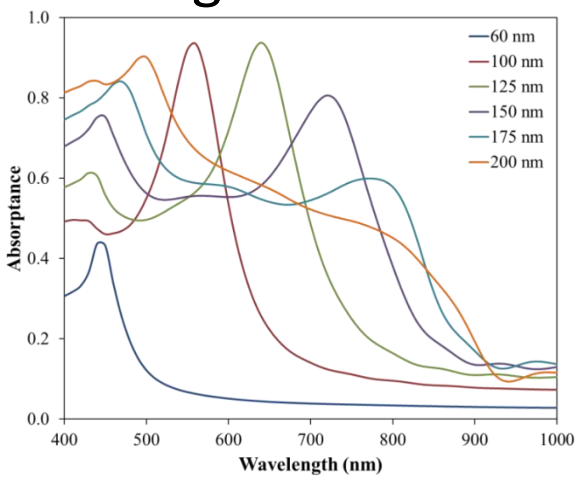


Nanotechnology 25 (2014) 305303

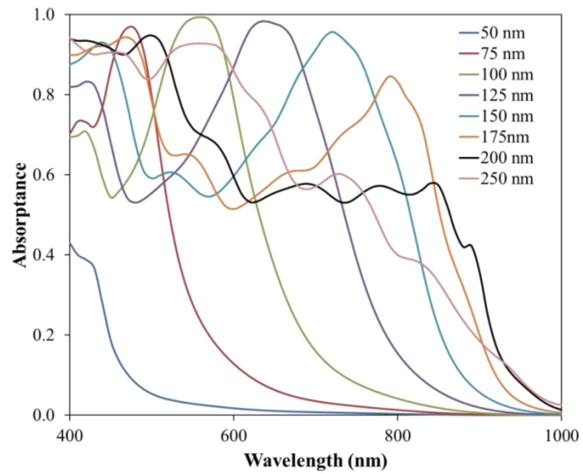
Nanowire Length Dependence

GaAs nanowires, Period: 400 nm

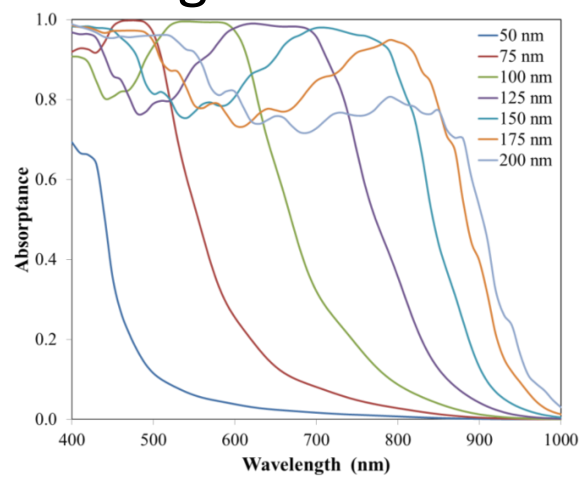
Length: 450 nm



Length: 1000 nm



Length: 2200 nm



Photodetectors
Power Convertors

Photovoltaics

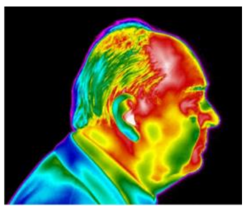
Nanotechnology 25 (2014) 305303
J. Appl. Phys. 112 (2012) 104311

Thin Film Multispectral Photodetectors

Military

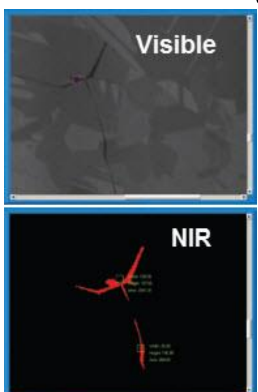
Night Vision

Biomedical



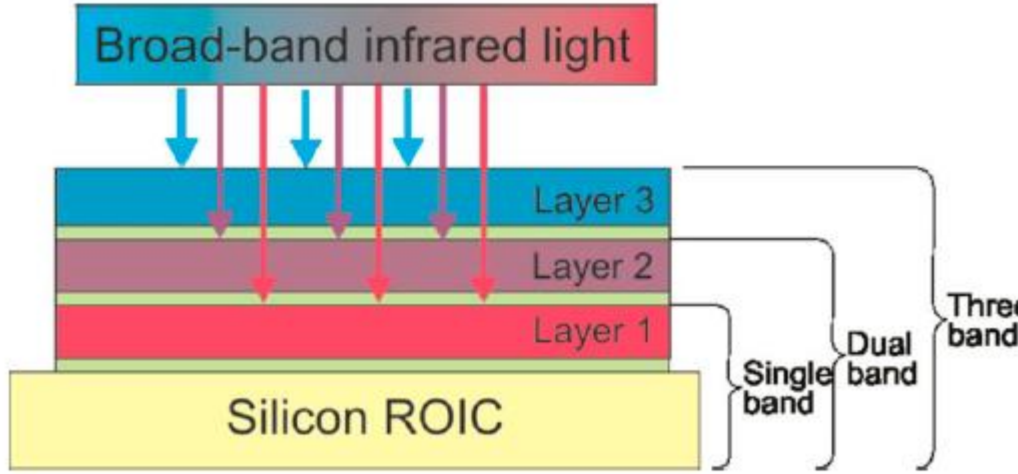
Search & Rescue

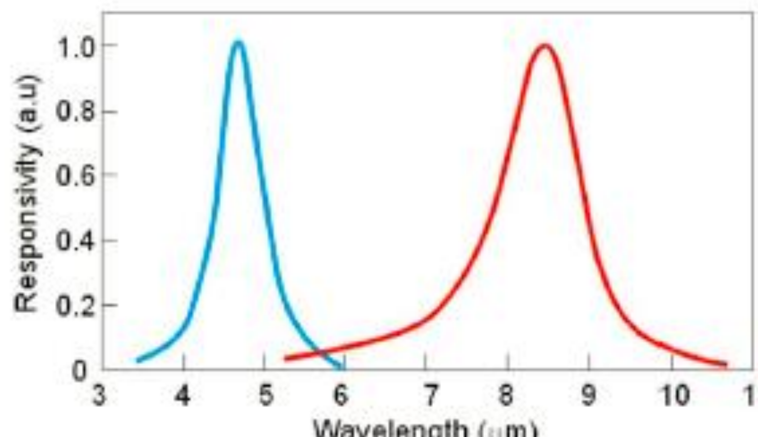
Manufacturing



Surveillance

IR Astronomy

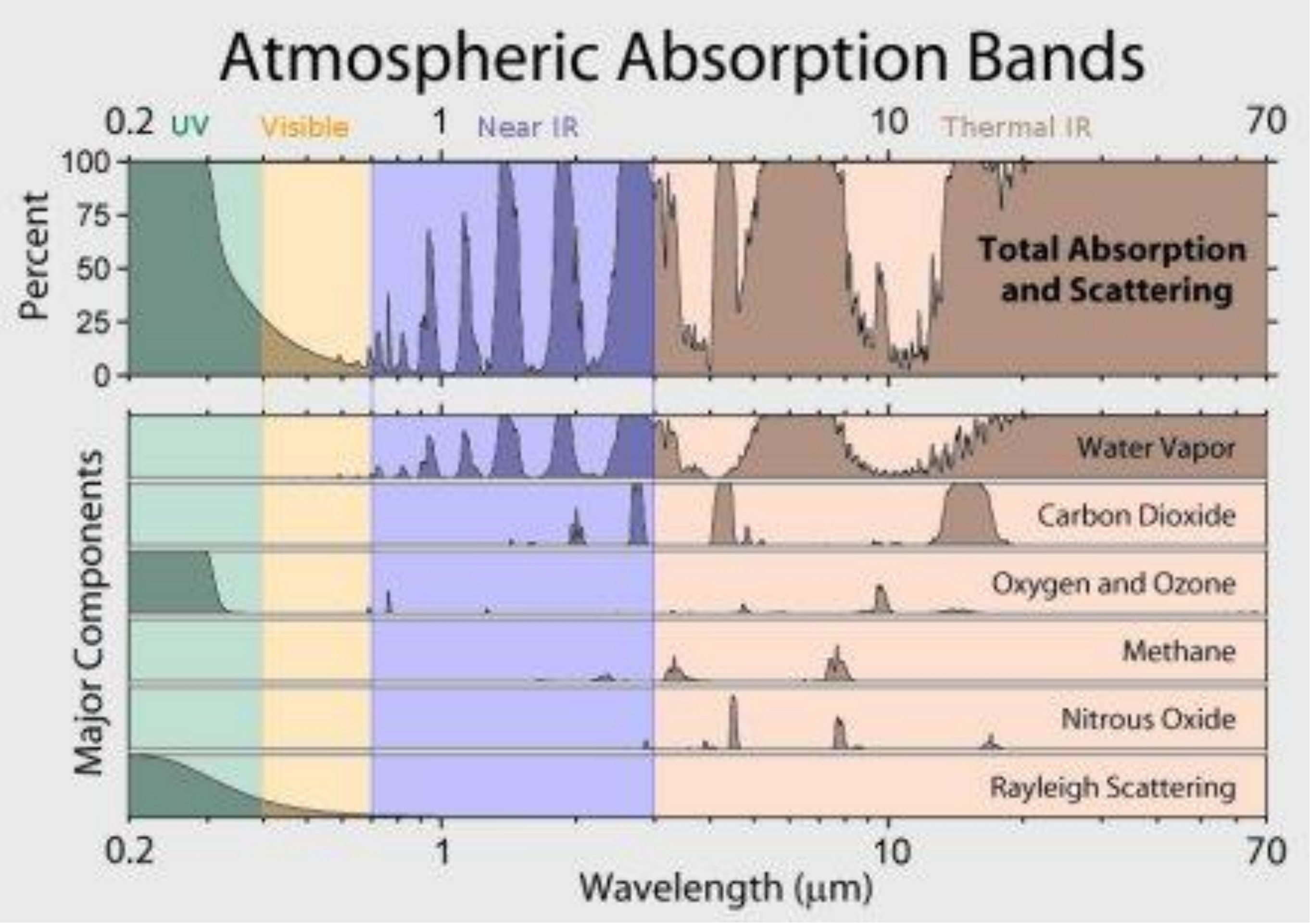




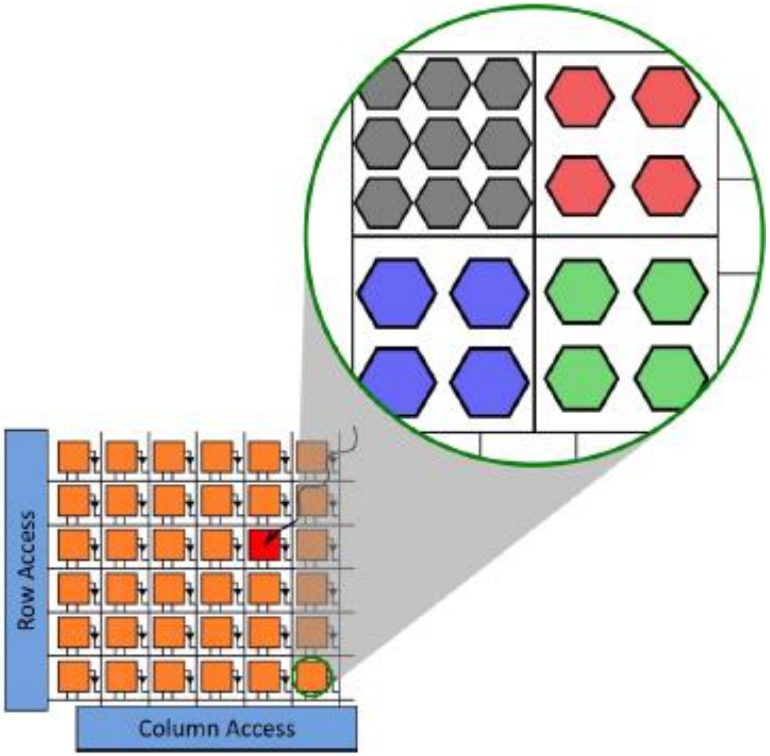
JAP 105 (2009) 091101

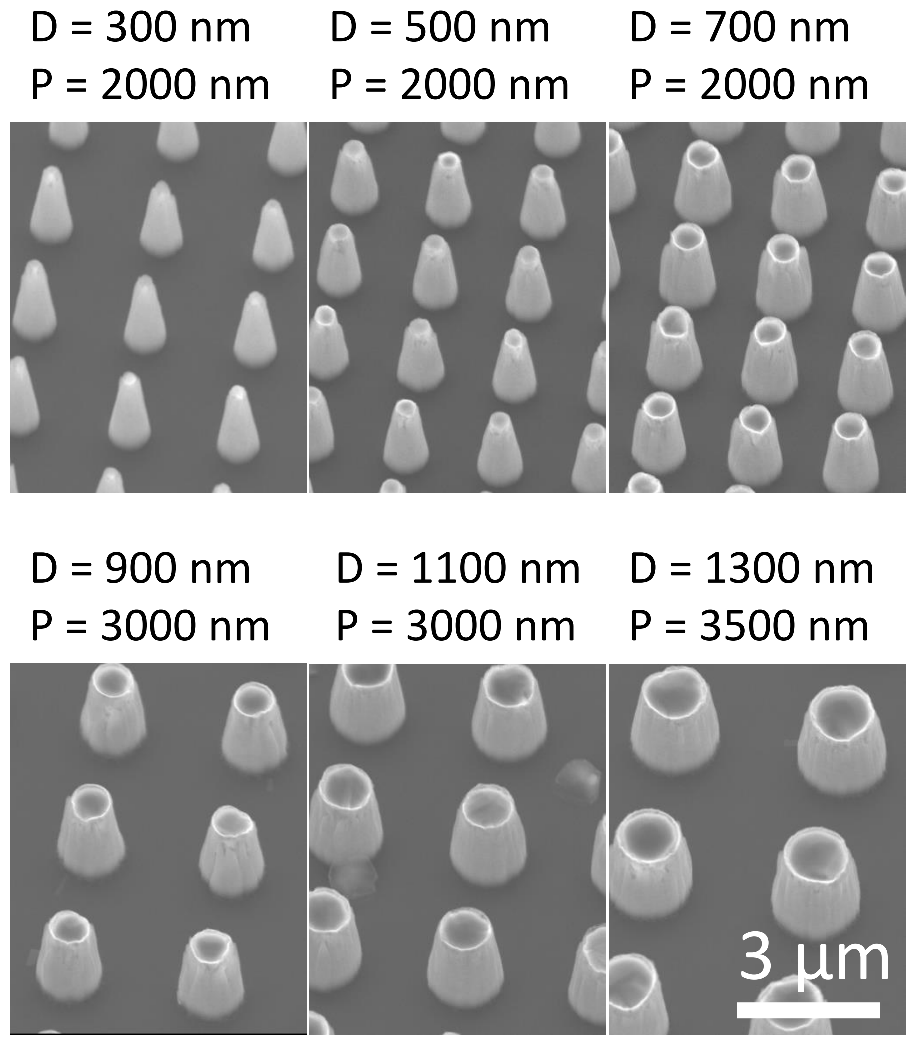
Optical Satellite Communications

- High Throughput and Secure Networks Challenge Program (HTSN)
- Quantum Encryption and Science Satellite (QEYSSAT)



InSb Nanowires/Pillars

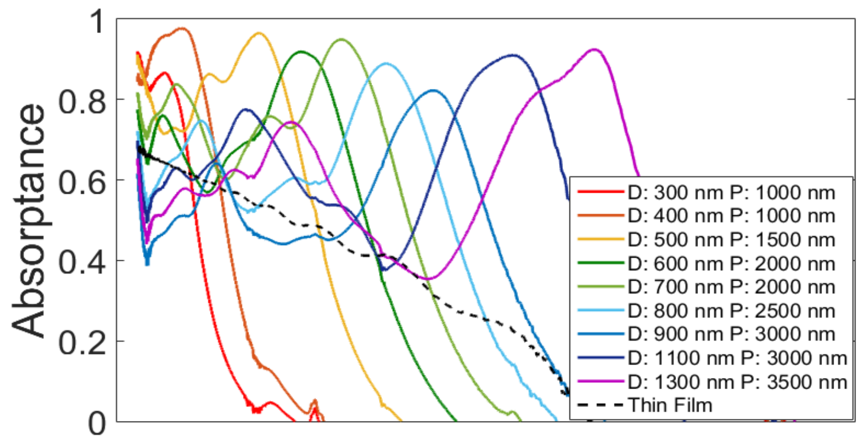




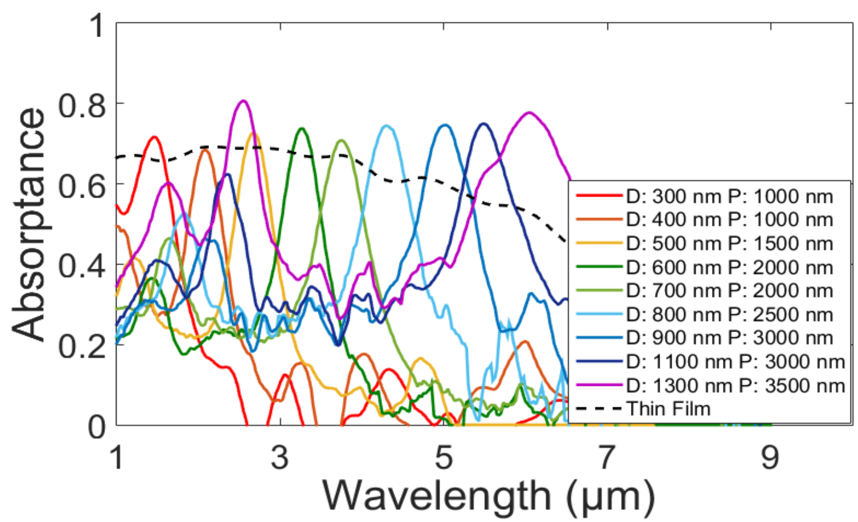
Semicond. Sci. Technol. 34 (2019) 035023

Mid-wavelength Infrared (MWIR) Multispectral Optical Absorption

InSb



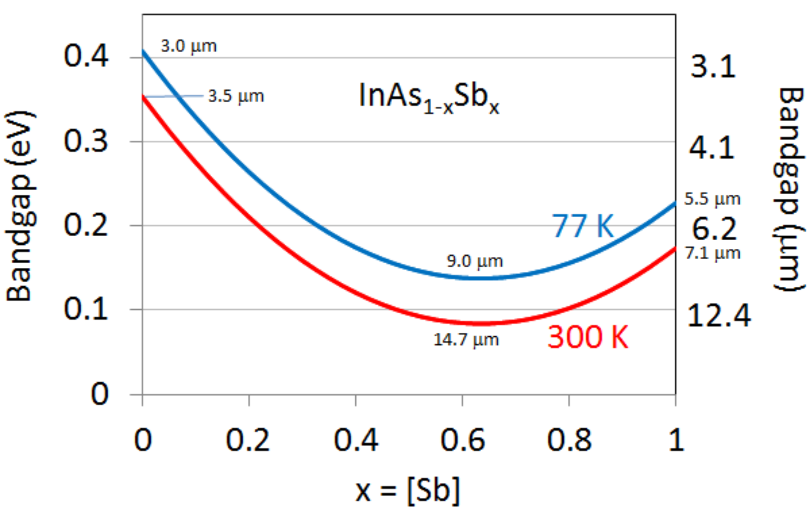
Experiment

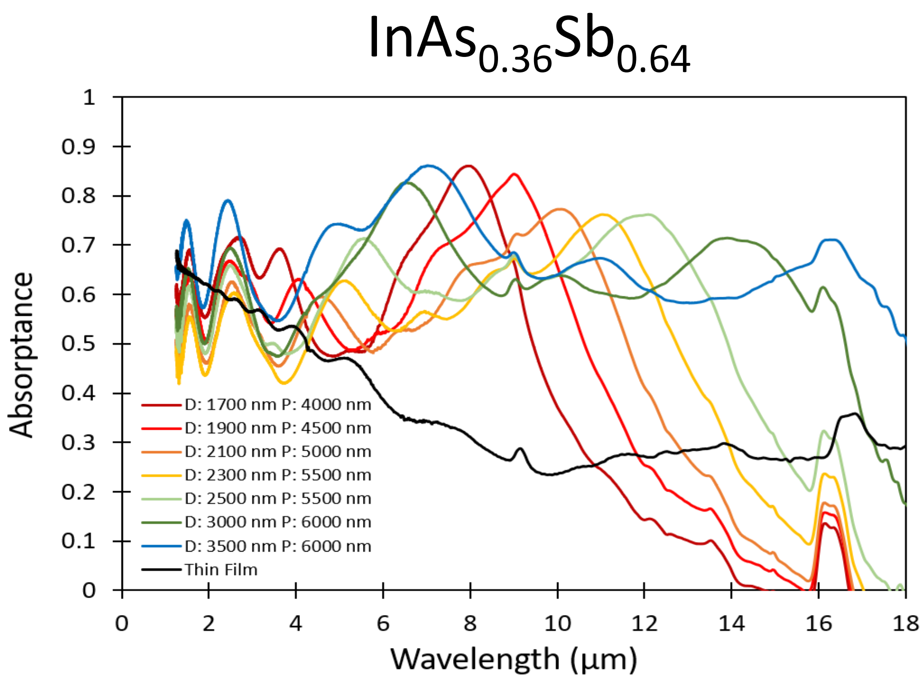


Simulation

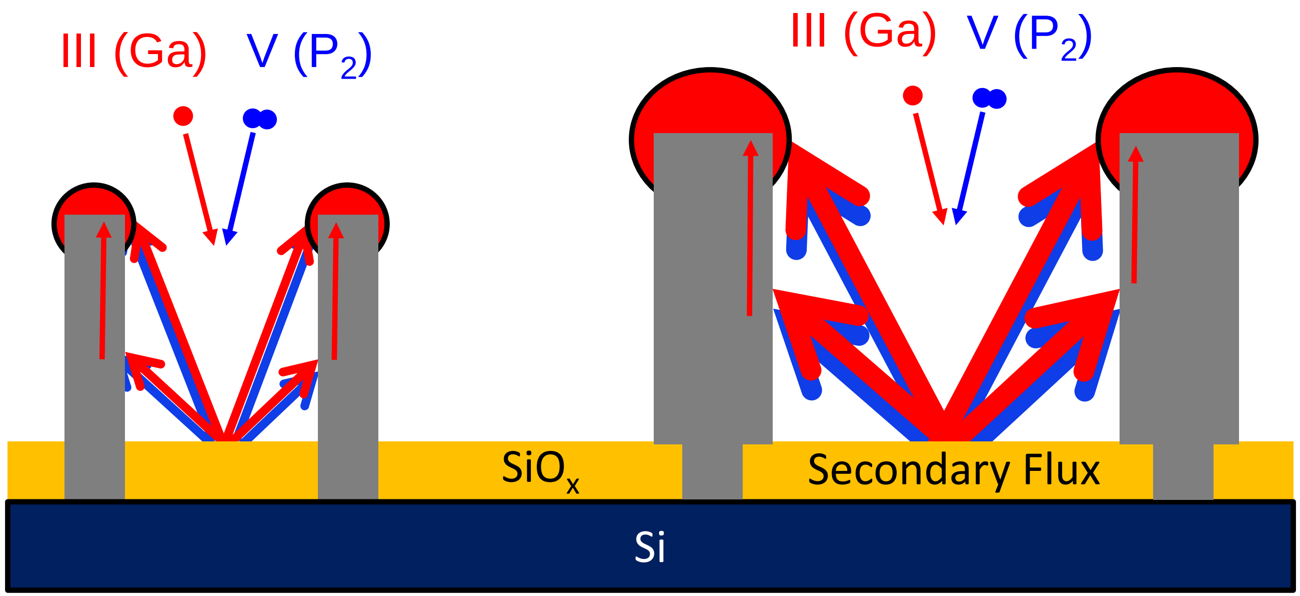
Semicond. Sci. Technol. 34 (2019) 035023

Long Wavelength Infrared (LWIR) Multispectral Optical Absorption



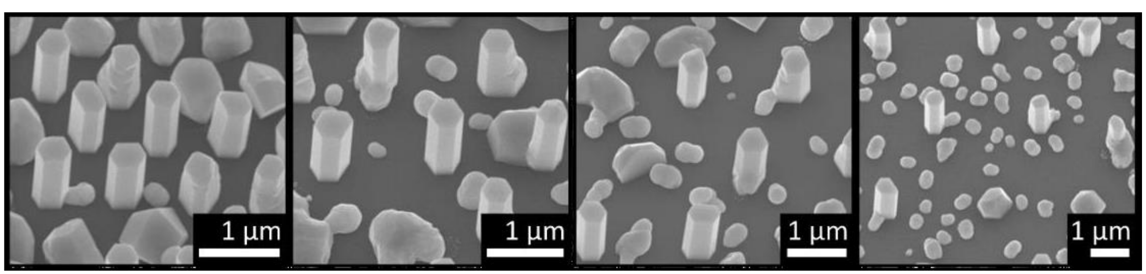


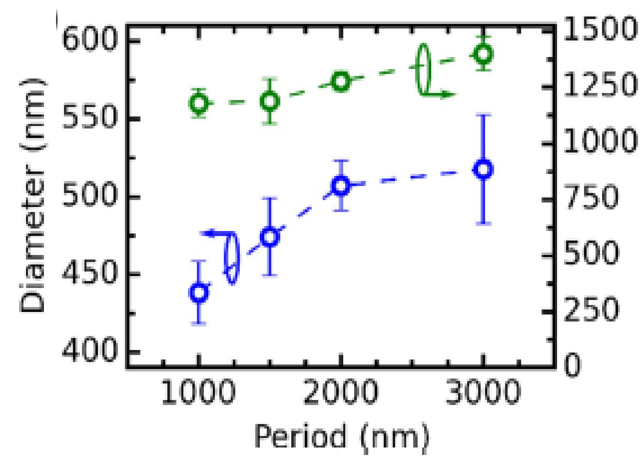
Multispectral Nanowire Growth



InSb:

P = 1000 nm	P = 1500 nm	P = 2000 nm	P = 3000 nm
D = 440 nm	D = 475 nm	D = 505 nm	D = 520 nm



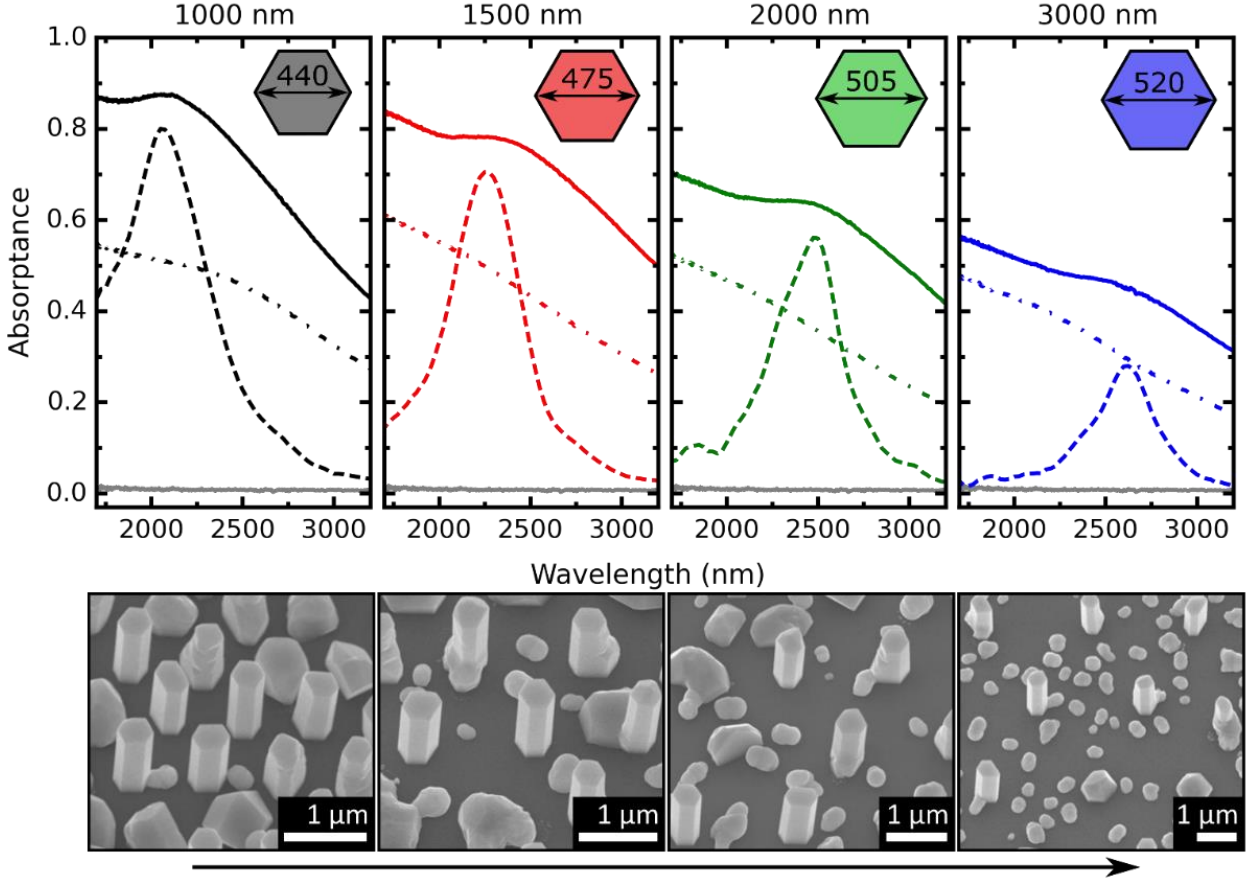


Increasing period → increasing diameter

Nano Futures 1 (2017) 035001

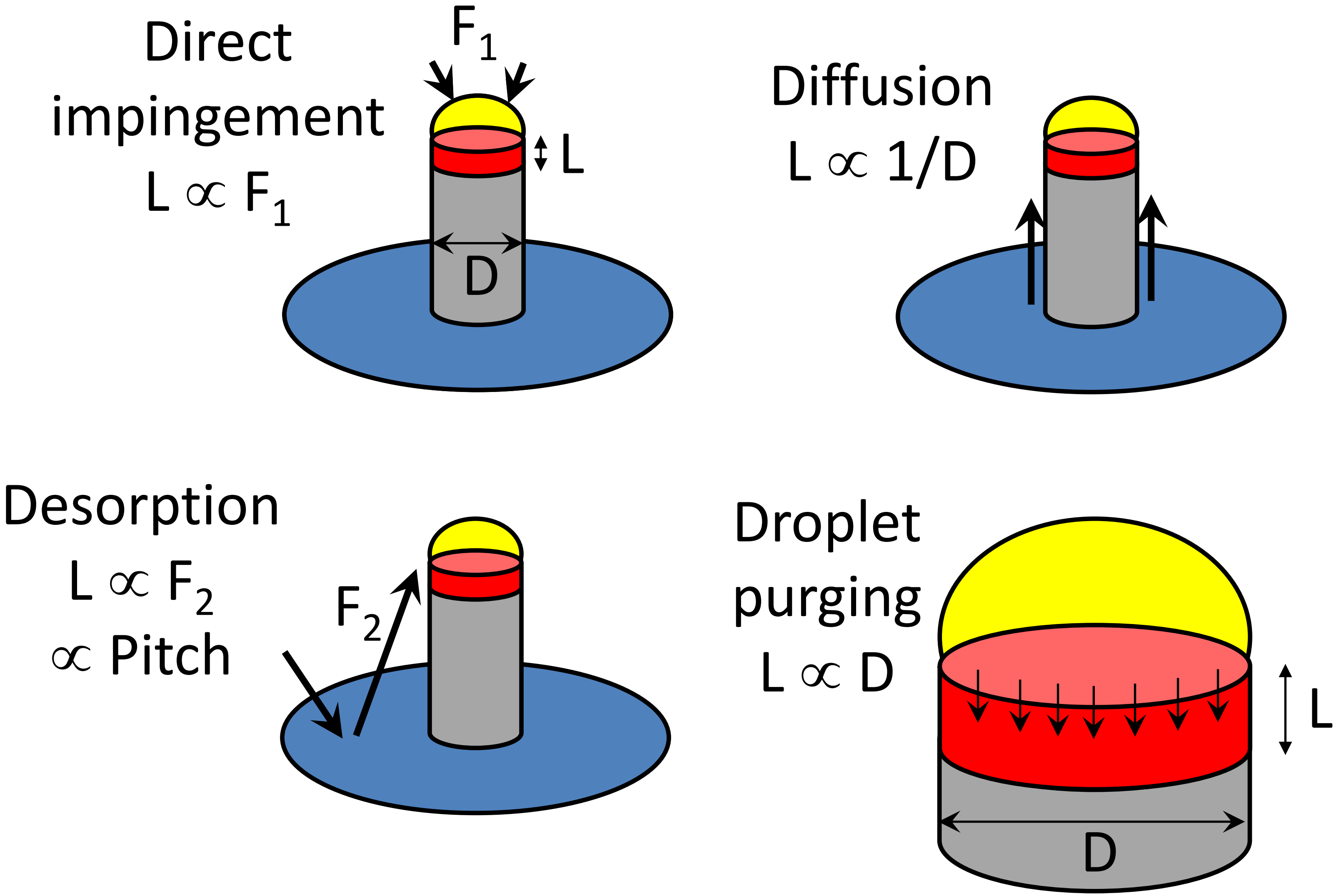
Increasing period → increasing diameter
→ Red-shift of absorptance

InSb

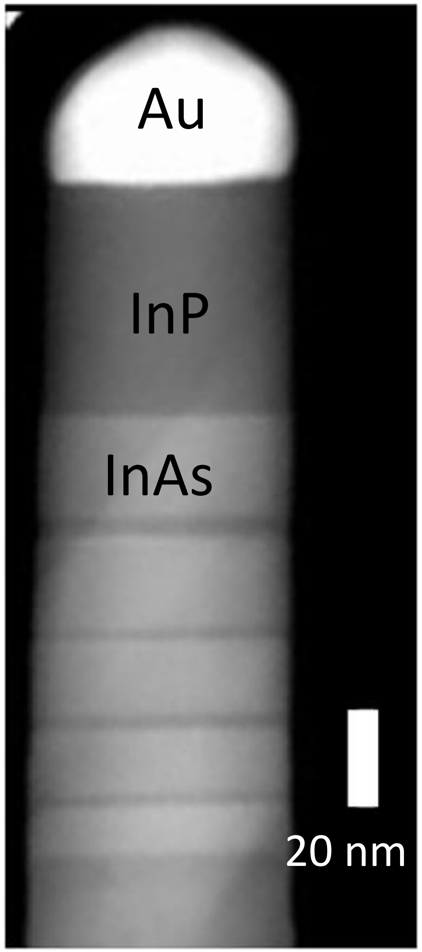


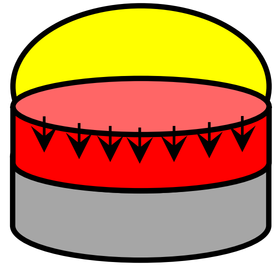
Nano Futures 1 (2017) 035001

Quantum Dot (QD) Growth Mechanisms

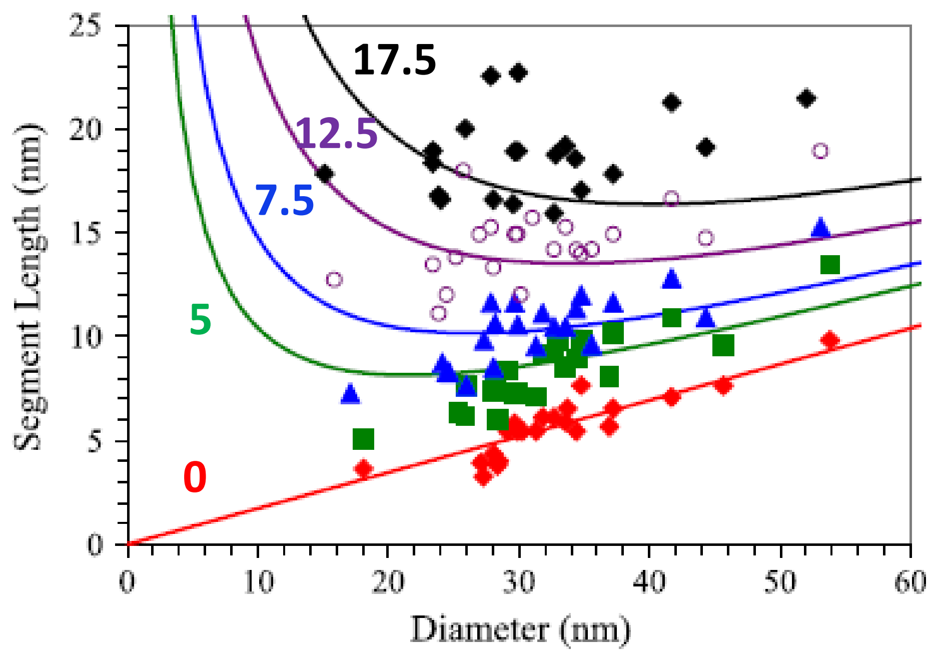


$InAs_xP_{1-x}$ QDs / InP



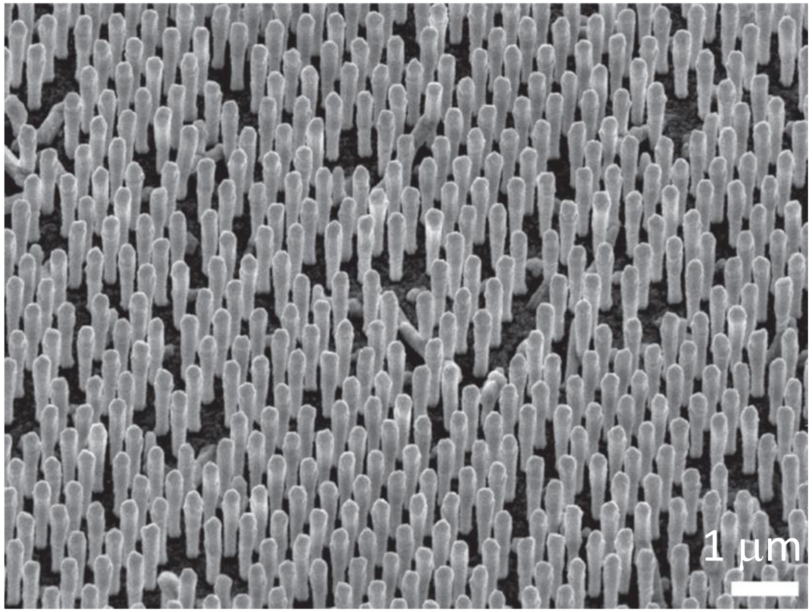


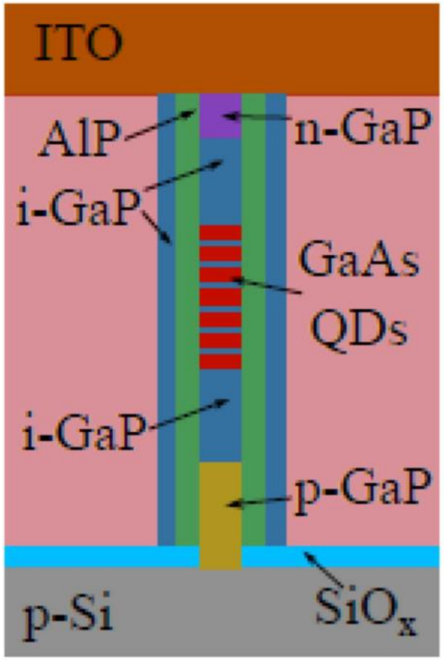
Droplet
purging
$L \propto D$

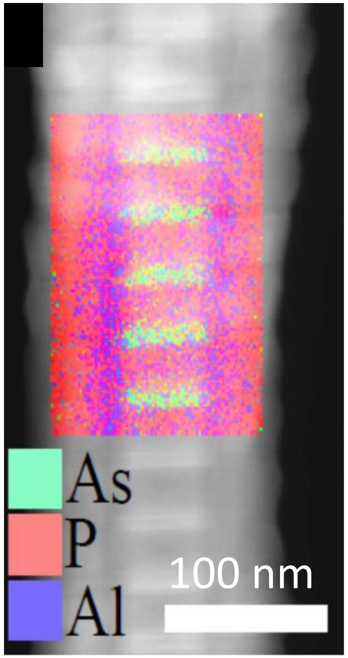


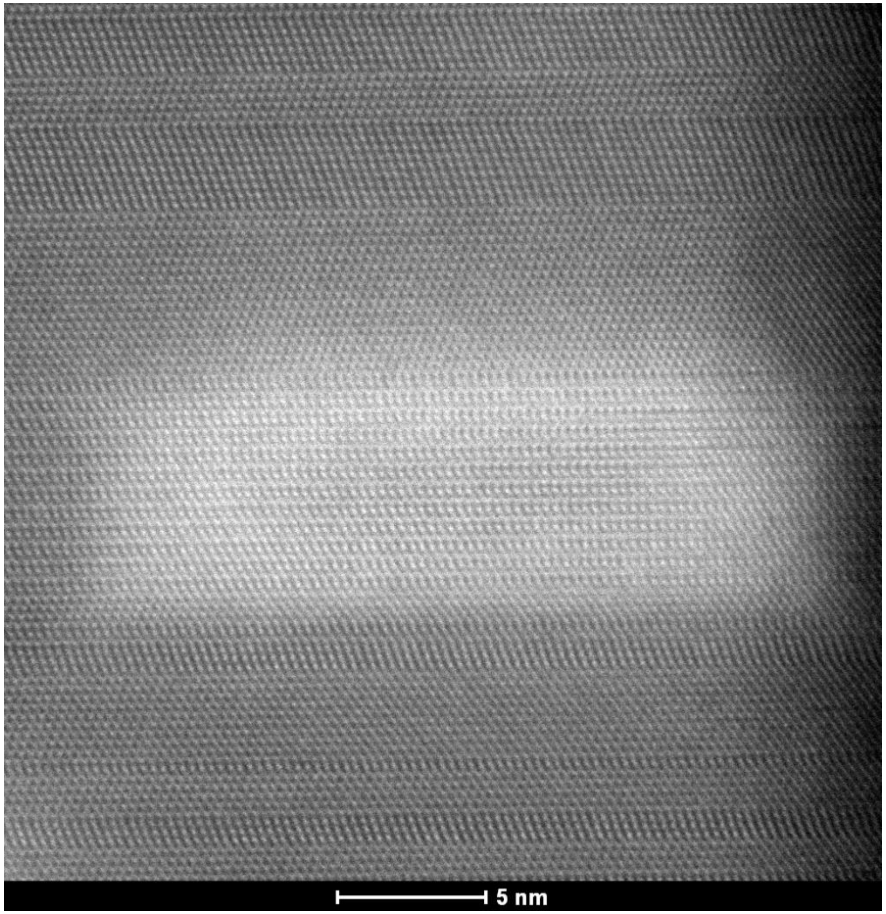
Nanotechnology 26 (2015) 315202

GaAs QDs / GaP



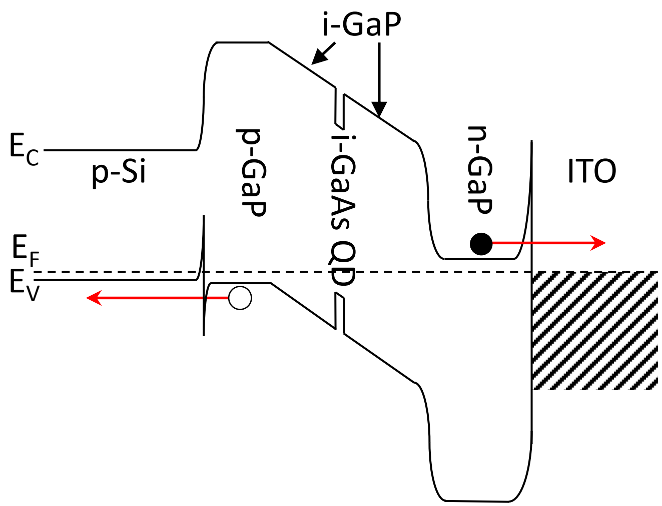


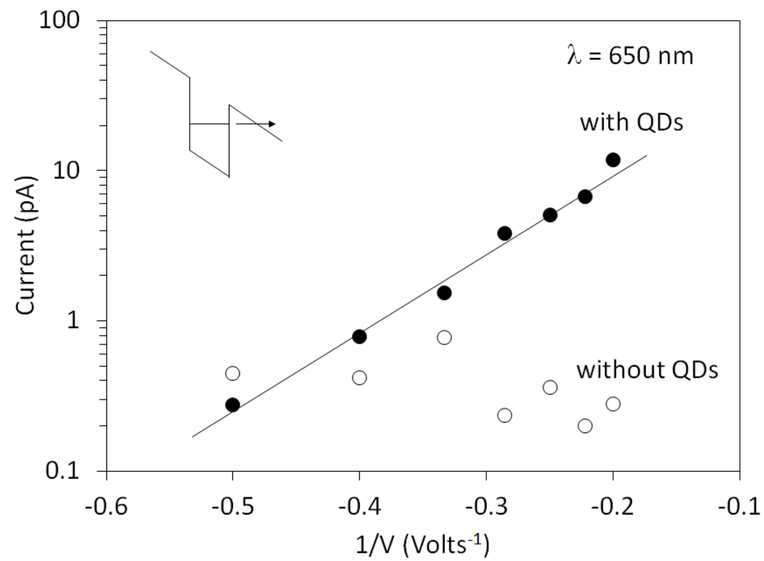




Nanotechnology 29 (2018) 124003

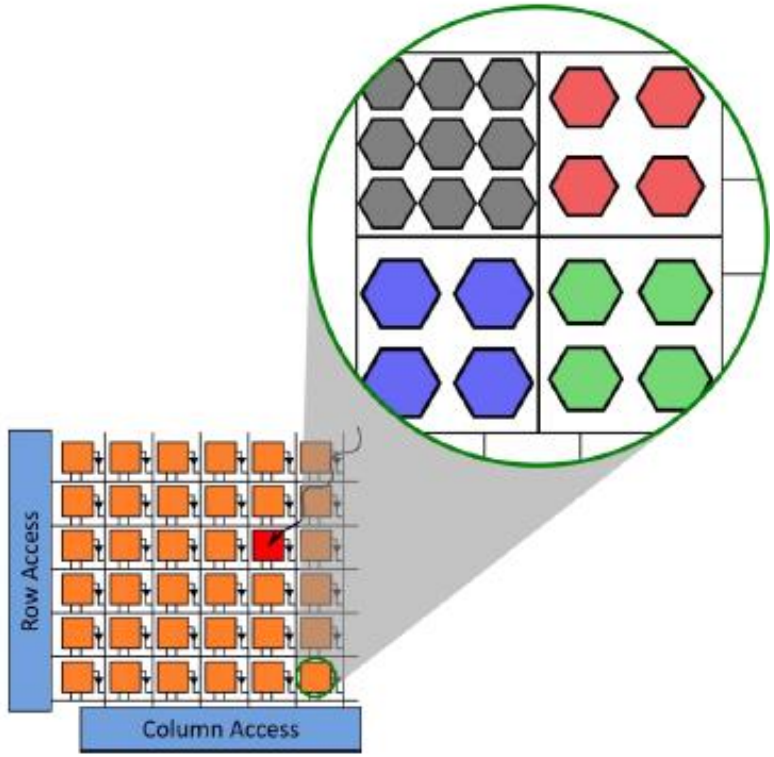
GaAs/GaP QD Photodetectors





Nanotechnology 29 (2018) 124003

Summary



- Small pixel size
  (single nanowire)
- Excellent light coupling
- High responsivity
  (better than thin films)
- Multispectral: Visible to LWIR
- Unique heterostructures
- Monolithic integration with Si

Acknowledgements

McMaster University

CEDT
Centre for Emerging Device Technologies

AECOM

LOCKHEED MARTIN

ccem
Canadian Centre for Electron Microscopy

TNFC
Toronto Nanofabrication Centre

UNIVERSITY OF WATERLOO

IQC Institute for Quantum Computing

NSERC CRSNG

Ontario Centres of Excellence
Where Next Happens

TELEDYNE DALSA
Everywhereyoulook™

morgansolar

- Paige Wilson, Ph.D.
- Ara Ghusakan, Ph.D.
- Nebile Isik, Research Engineer
- Amanda Thomas, M.A.Sc.
- Curtis Goosney, M.A.Sc.