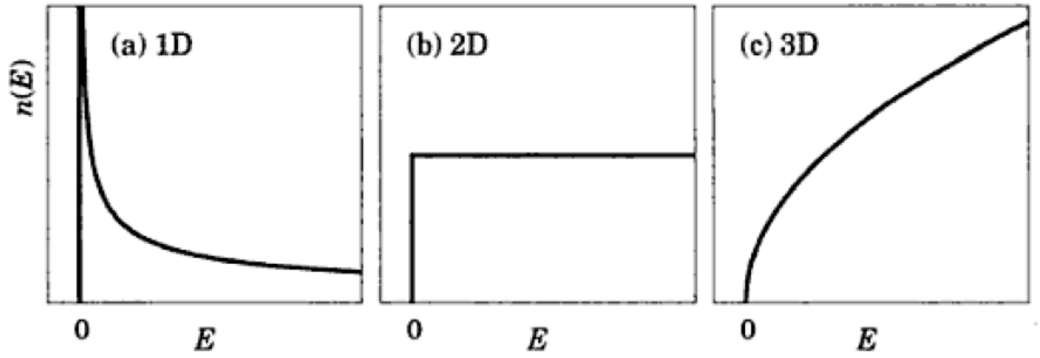
Class 12
Low dimensional devices

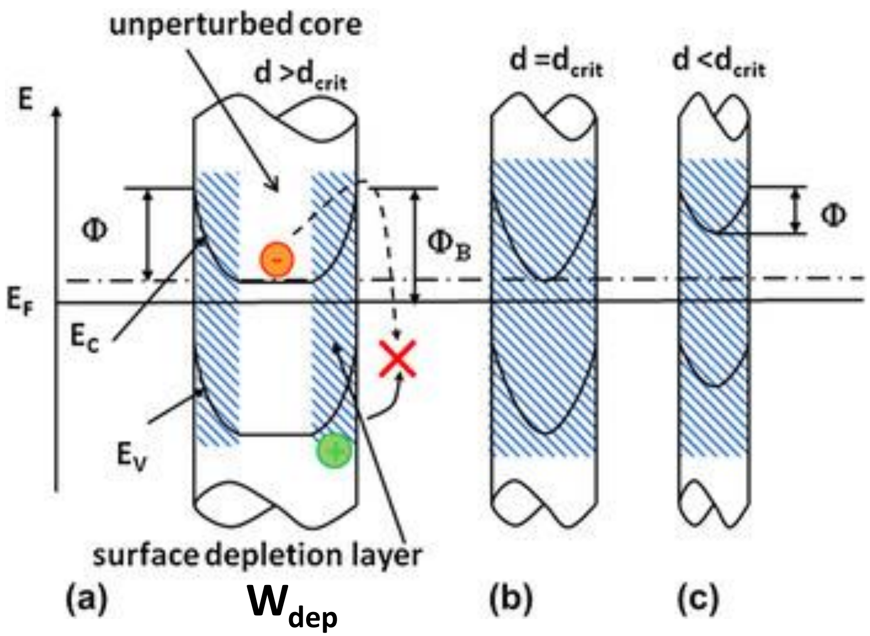
29.04.2024

- Generals
- 2D devices:
  - TMDs photodetectors
- 1D devices:
  - Nanowire solar cells
  - Nanowire LEDs
- 0D devices:
  - QD-LEDs
  - Coulomb blockade

Low dimensional materials: key aspects

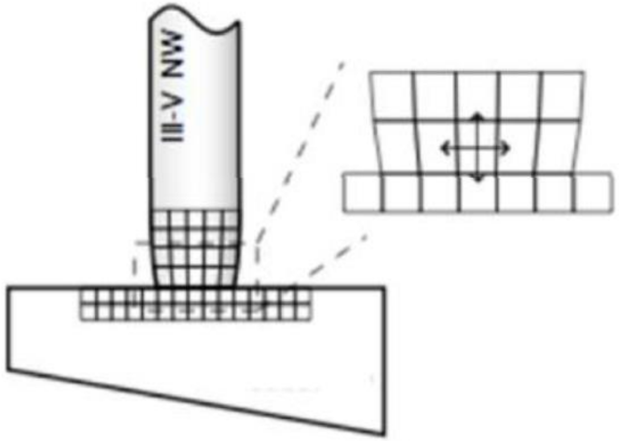
Quantum confinement

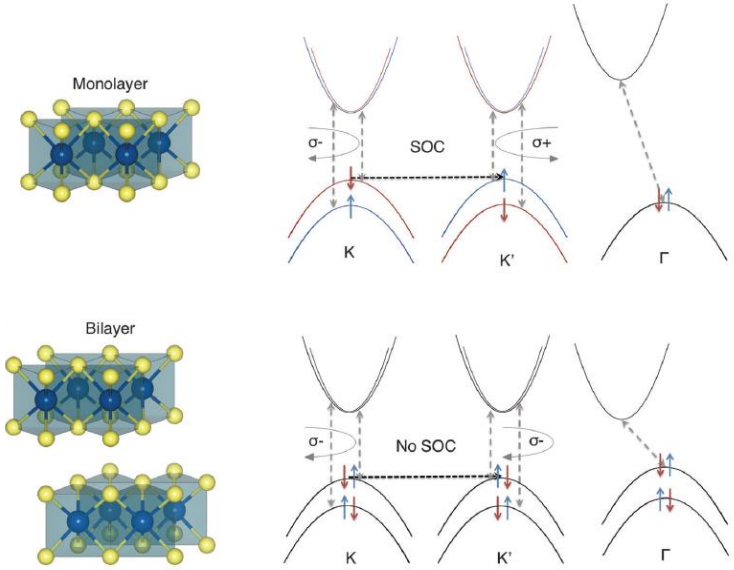




Surface/Volume ratio

Heterostructuring and material integration

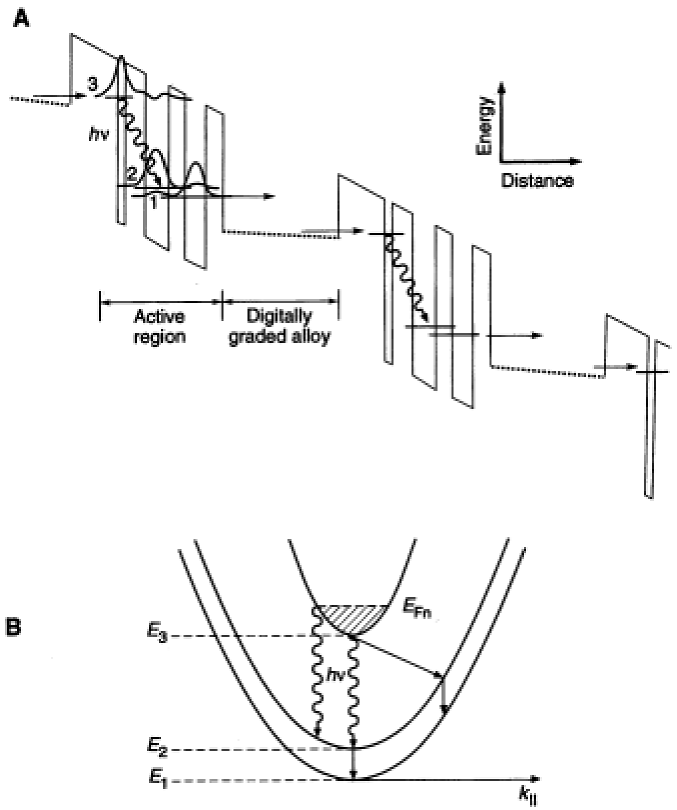




Layer-by-layer engineering

Quantum wells in optoelectronic devices: examples

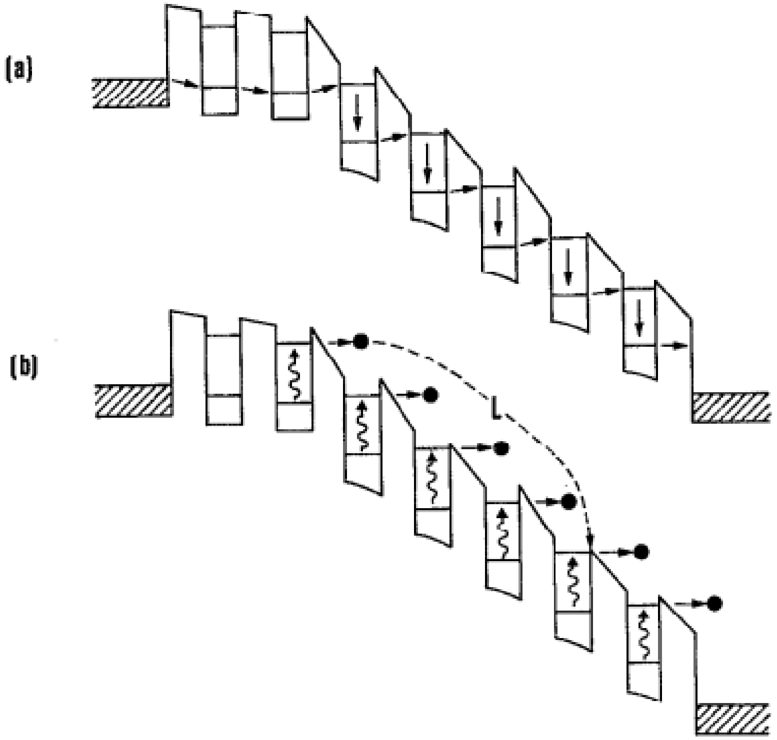
Quantum cascade lasers (QCLs)



Jerome Faist *et al.*, *Science,* 264,553-556 (1994)

DOI:10.1126/science.264.5158.553

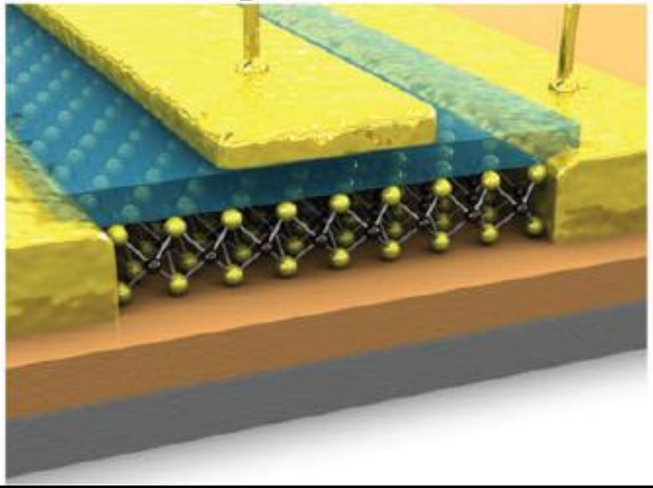
Quantum well IR photodetectors



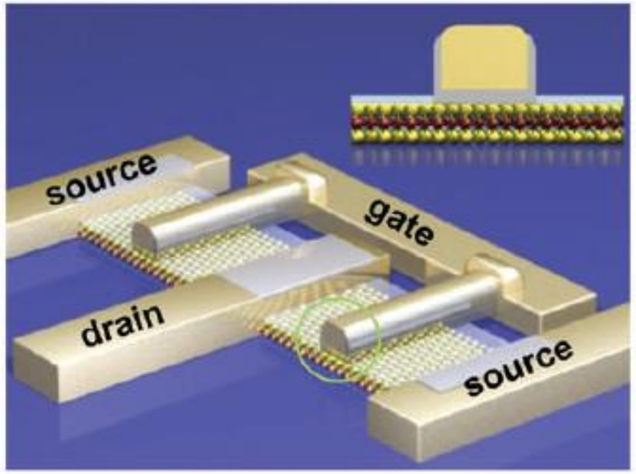
Levine, B. F., *Journal of applied physics* 74, 8 (1993)

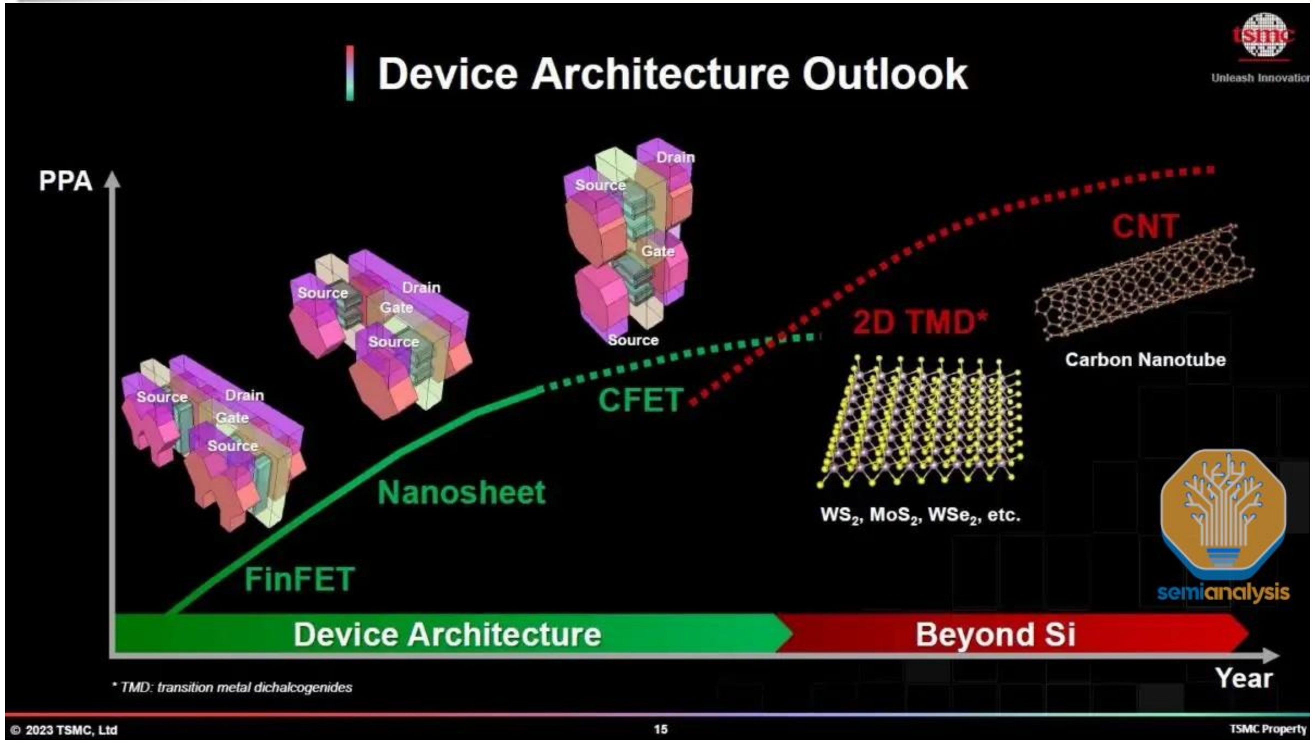
DOI: 10.1063/1.354252

MoS_2 Single channel



MoS_2 Dual Channel



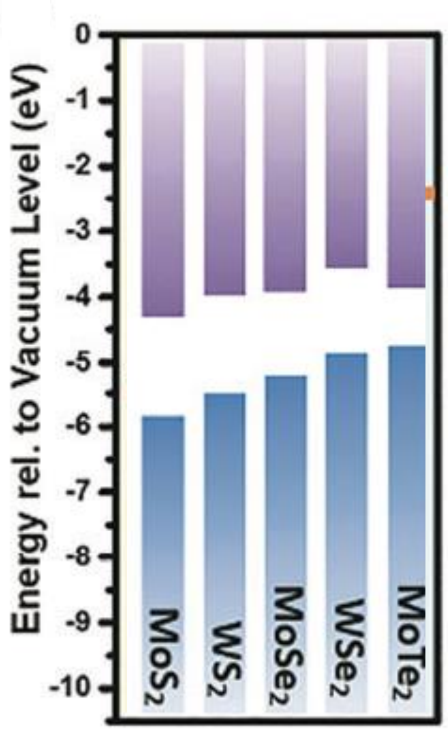


2D devices

Duan et al., Chem. Soc. Rev.,44, (2015)

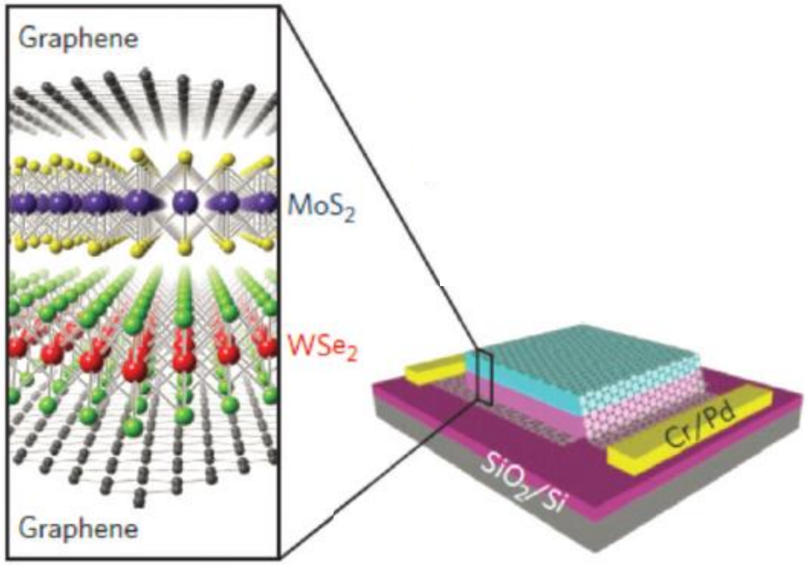
https://semianalysis.com/2024/01/03/intel-genai-for-yield-tsmc-cfet-and/

2D Heterostructures



Depending on the band alignment, functional properties can be exploited in different ways

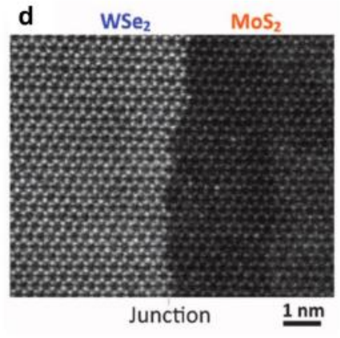
Vertical HJs (Stacks)



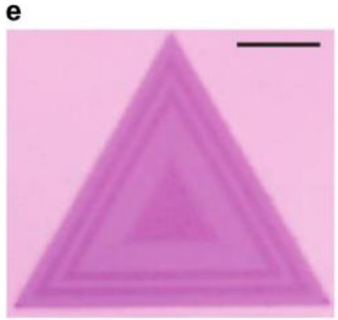
Graphene
MoS_2
WSe_2
Graphene

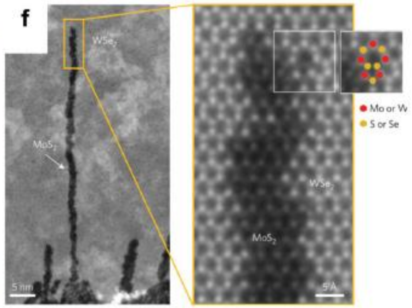
Planar (Lateral) HJs

Lateral junction

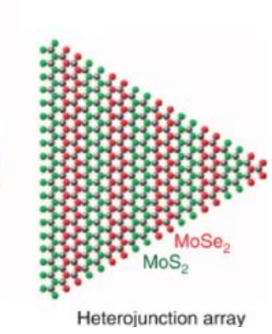


Triangular Junction





1D planar channel

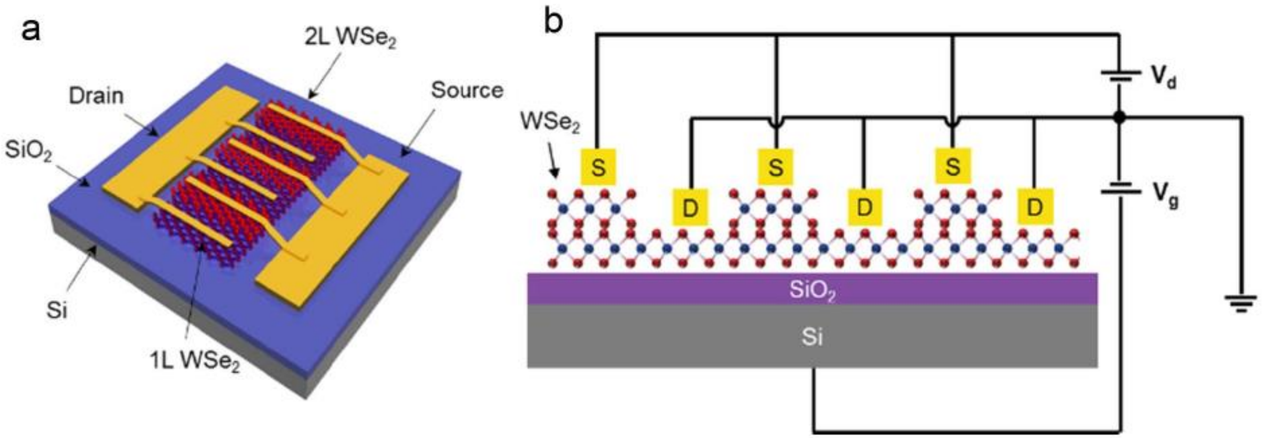


2D superlattice

Stanford et al., npj 2D Mat. and Appl. 2(20), (2018)

Exploiting Lateral HJs: 1L/2L photodetectors

Interdigitated 1L/2L WSe_2 photodetector

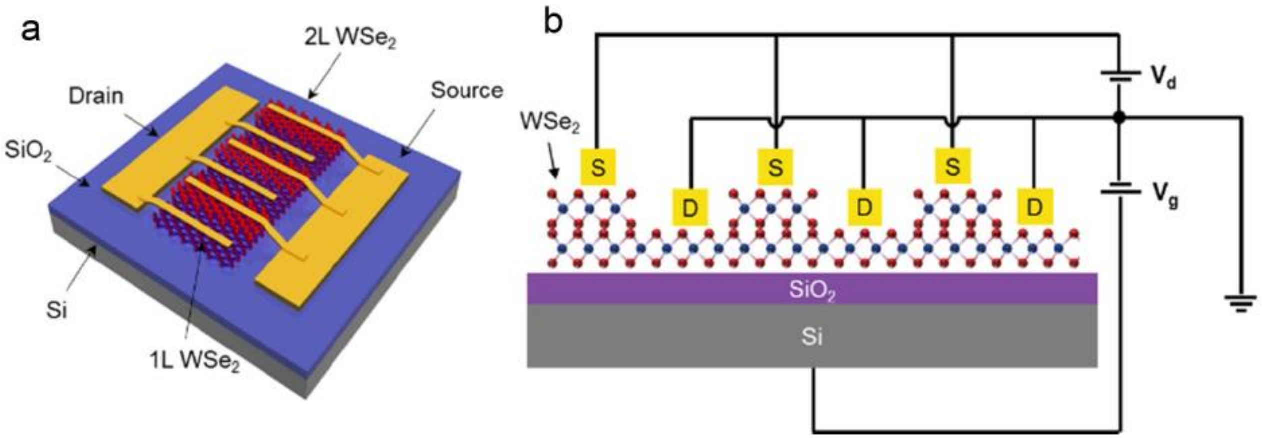


Is this a homojunction or a heterojunction?

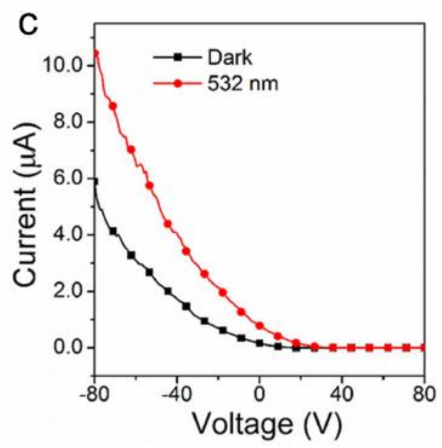
Xu et al., 2D Mater. 3 (2016)

Exploiting Lateral HJs: 1L/2L photodetectors

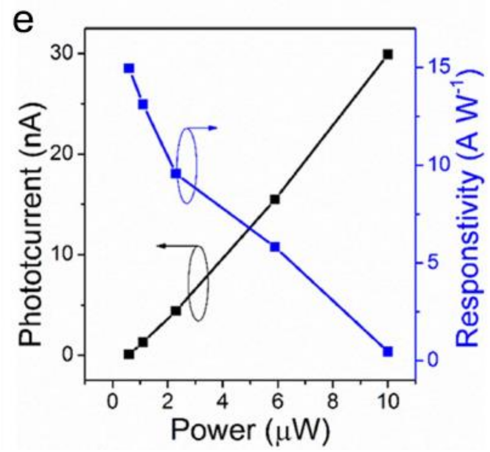
Interdigitated 1L/2L WSe_2 photodetector



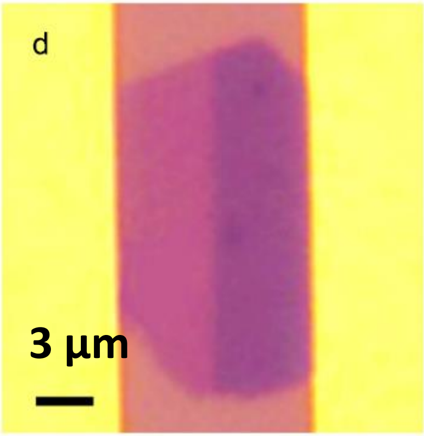
I(V)



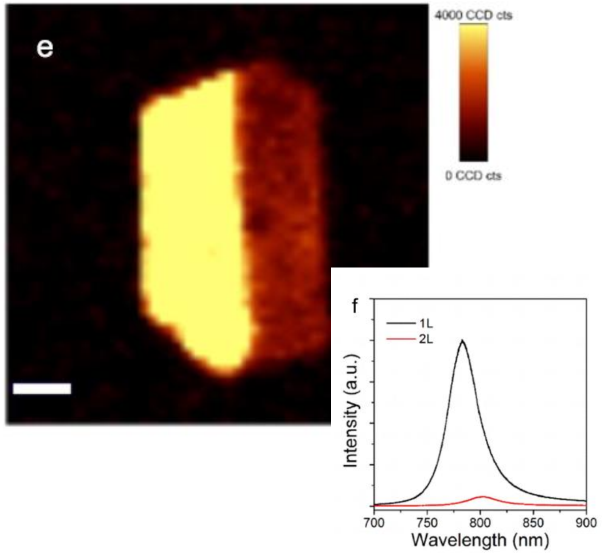
Photocurrent



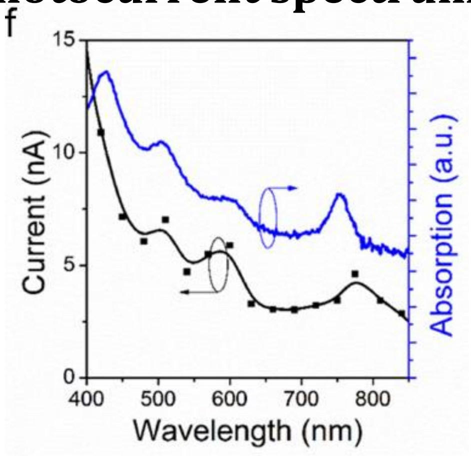
Optical Image



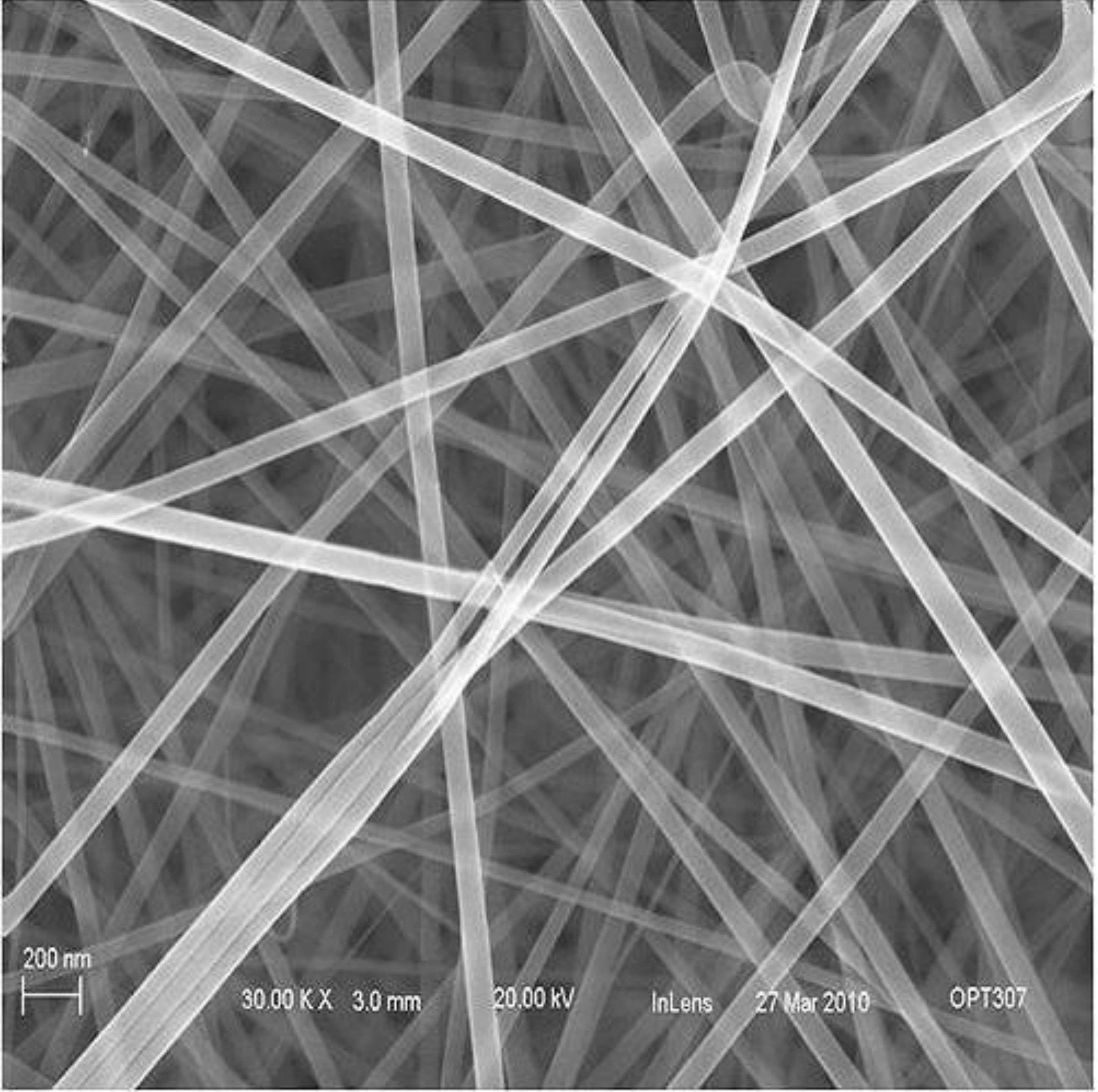
PL



Photocurrent spectrum



Xu et al., 2D Mater. 3 (2016)

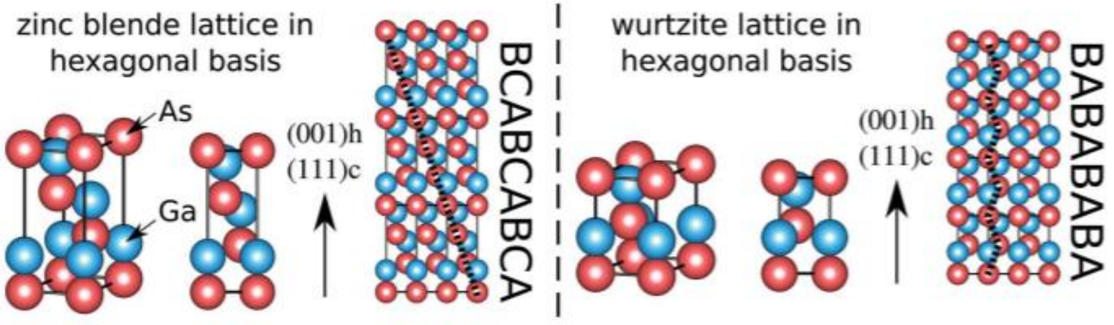


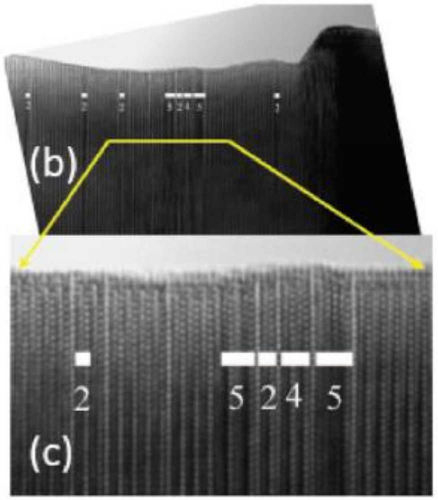
1D nanostructures
or
Nanowires

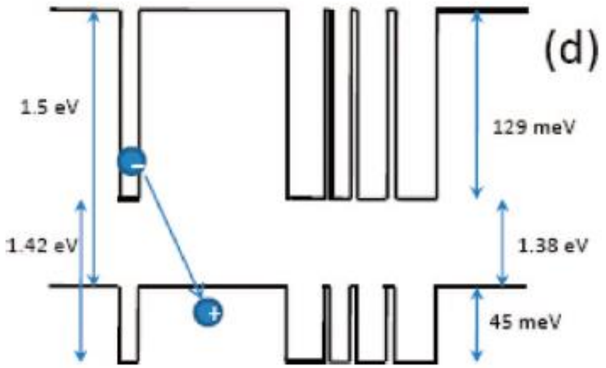
https://www.indiamart.com/proddetail/silicon-nanowires-20702670833.html

Advantages of Nanowires (1)

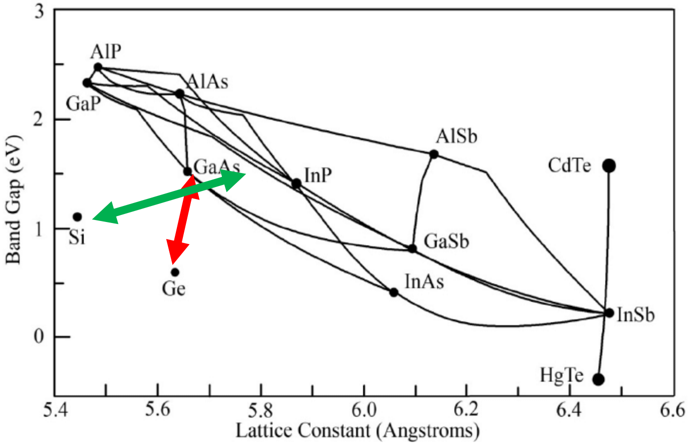
New phases =
Material engineering

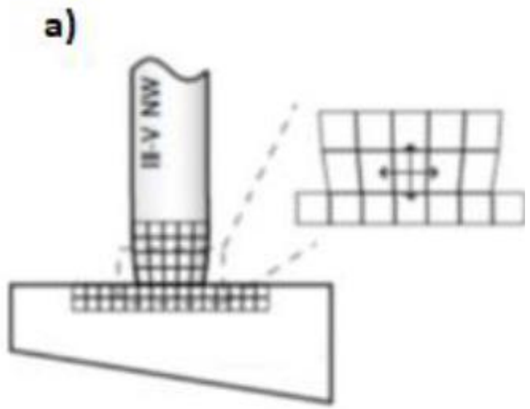


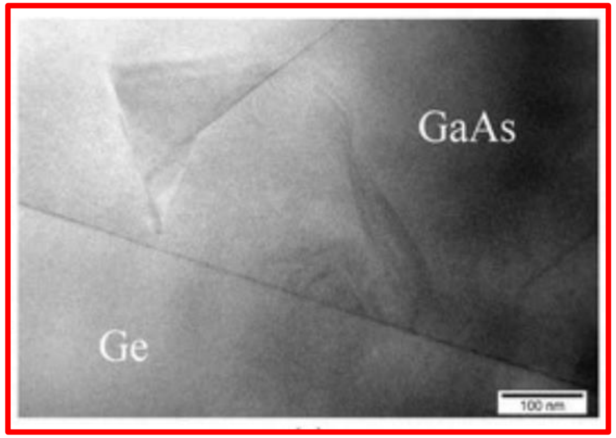


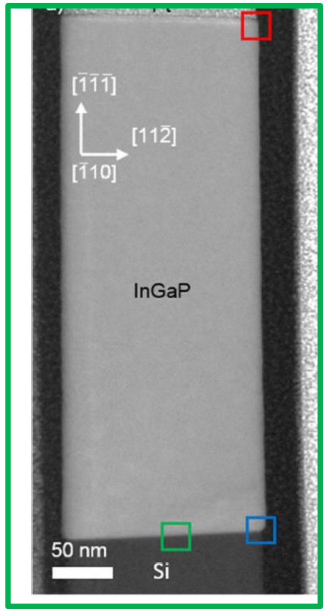


Stress relaxation = Low defect
density/Monocrystalline



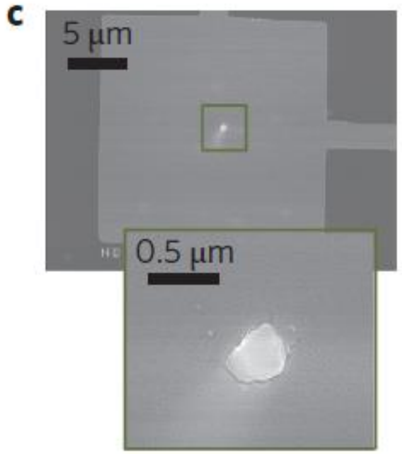


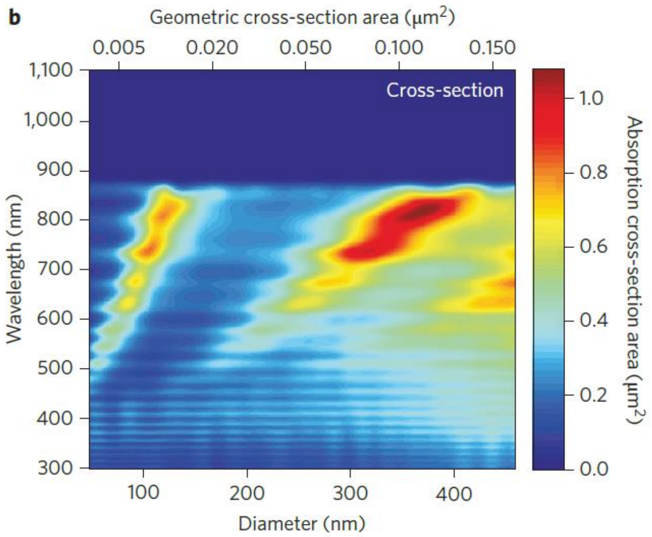


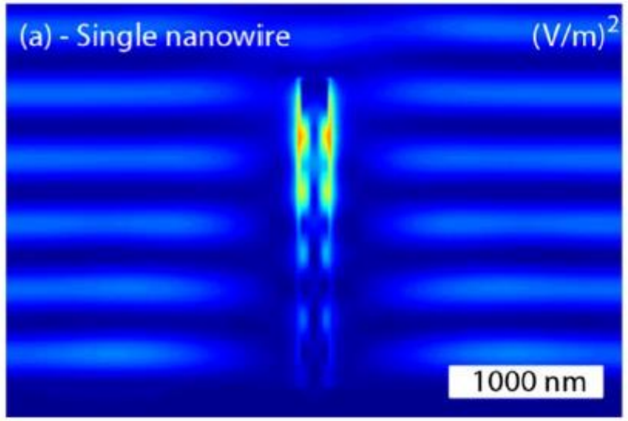


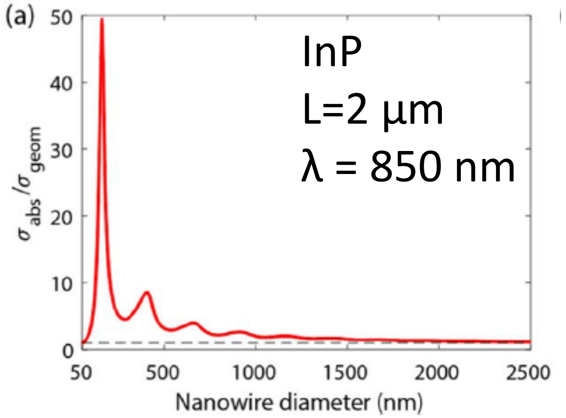
Advantages of Nanowires (2)

Enhanced Optical Absorption

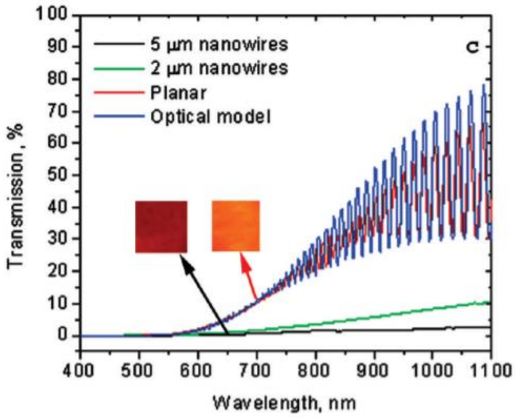


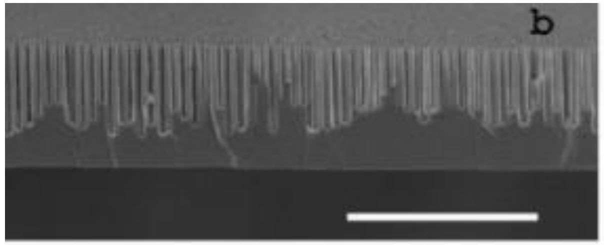




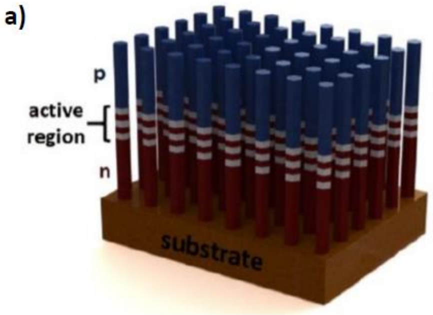


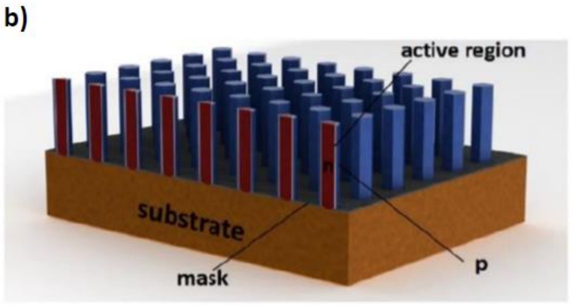
Light Trapping





3D Architectures

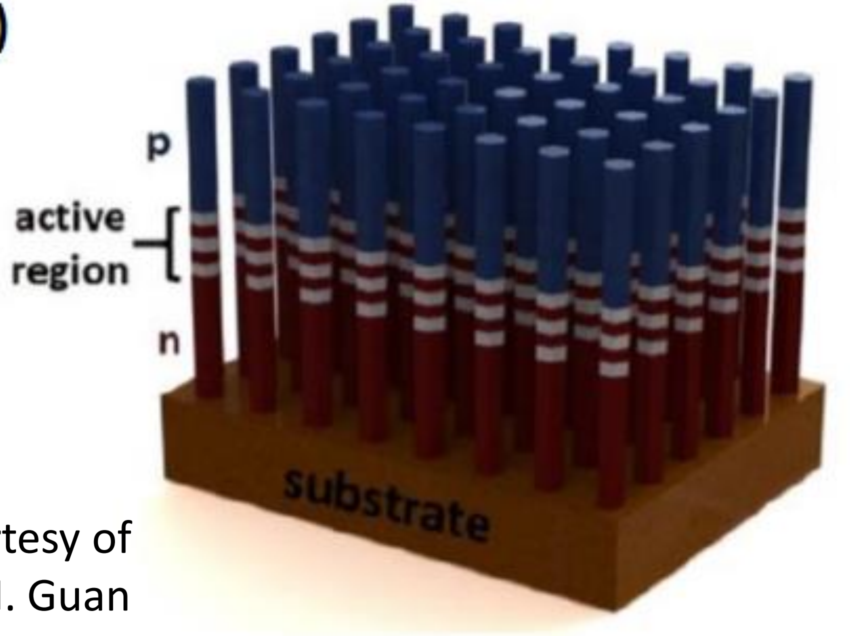




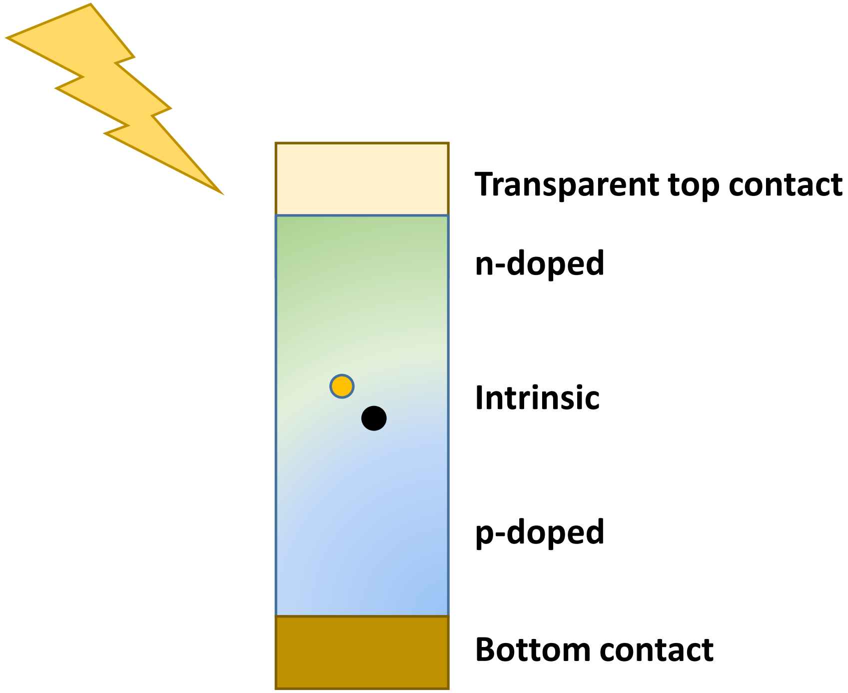
Junctions in Nanowires

AXIAL JUNCTION

a)



Courtesy of
Dr. N. Guan



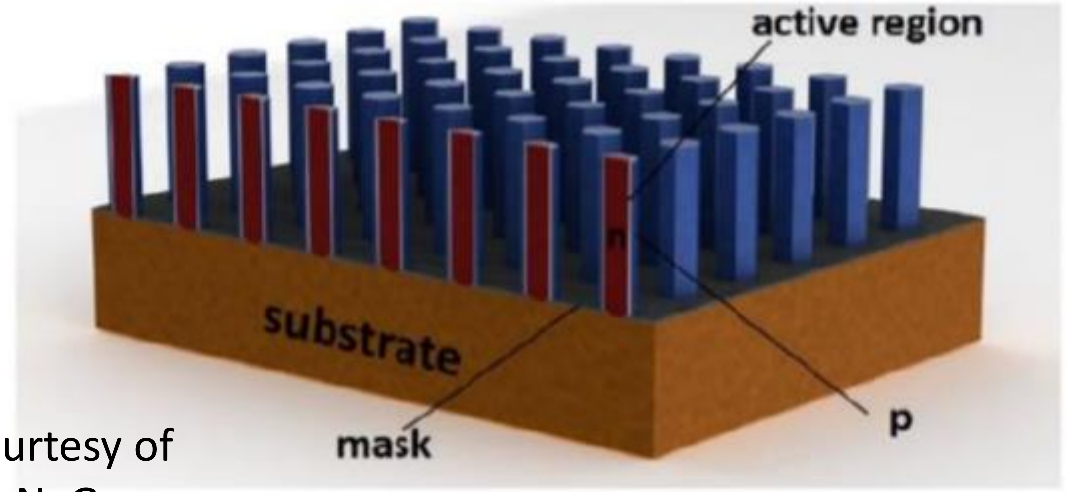
ADV.
- Photonic improvement
- Material Stacking
- Easy Fabrication
- Easy Modeling
- Easy Contacting

DIS.
- Surface effects
- Intermixing
- Junction area = Cross-section

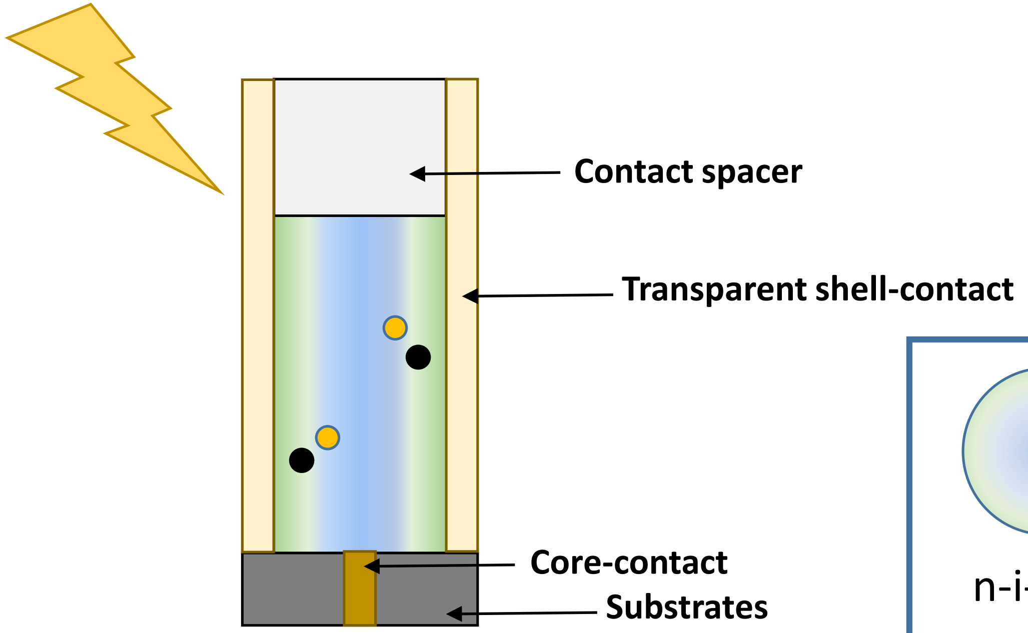
Junctions in Nanowires

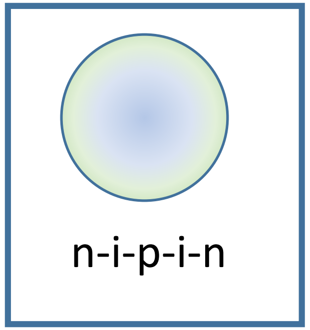
RADIAL JUNCTION (CORE-SHELL)

b)



Courtesy of Dr. N. Guan





ADV.

- Photonic improvement
- Material Stacking
- Junction area = $r_c * h$

- hν absorption ⊥ carrier splitting
- Surface passivated (core)
- No intermixing

DIS.

- Complex Fabrication
- Complex Modeling
- Complex Contacting

Benefits
Reduction in minority-carrier lifetime
Reduced material usage
Reduced reflectivity

Challenges
Positional stability of dopants
Achieving high areal density
Top contact

Nanowires-based Solar cells (1)

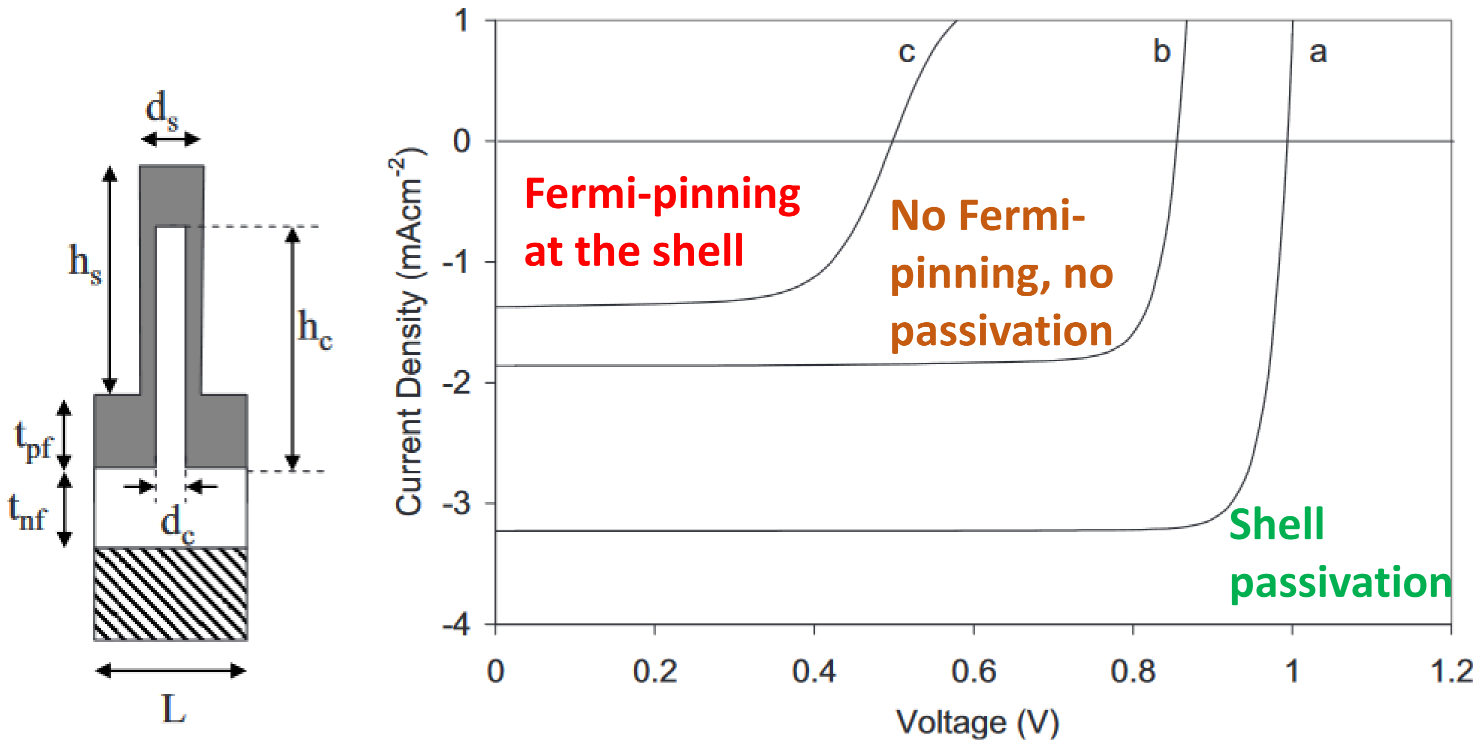


FIG. 2. Model J-V characteristics for (a) top contact with sidewall passivation; (b) top contact without sidewall passivation using $S=5\times10^{6}$ cm s^{-1} and $D=10^{12}$ cm^{-2}; and (c) sidewall contact with Fermi level pinning at midgap.

Additional parameters:

- Nanowire geometry
- Surface recombination rate
- Doping level core and shell
- p-n or p-i-n junction

R.R.LaPierre, J. Appl. Phys. 109, 034311 (2011)

Nanowires-based Solar cells (1)

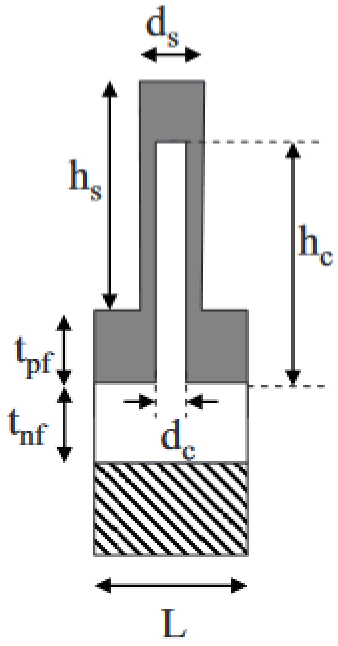


TABLE II. Summary of solar cell performance.

Type of cell	V_{oc} (V)	J_{sc} [a] ($mA\ cm^{-2}$)	FF	η [a] (%)
(1) Top contact with passivation	0.99	3.23 (21.8)	0.88	2.82 (19.0)
(2) Top contact without passivation	0.86	1.86 (12.5)	0.84	1.34 (9.0)
(3) Sidewall contact	0.49	1.38 (9.3)	0.68	0.46 (3.1)
(4) Top contact with passivation, reduced shell height, $N_a=N_d=5\times10^{19}$ cm^{-3}	1.04	4.51 (30.5)	0.89	4.17 (28.1)
(5) p-i-n structure, top contact with passivation, reduced shell height, $N_a=N_d=5\times10^{19}$ cm^{-3}	1.04	10.7 (29.6)	0.88	9.81 (27.3)
(6) Record planar GaAs cell[b]	1.045	29.6	0.85	26.1

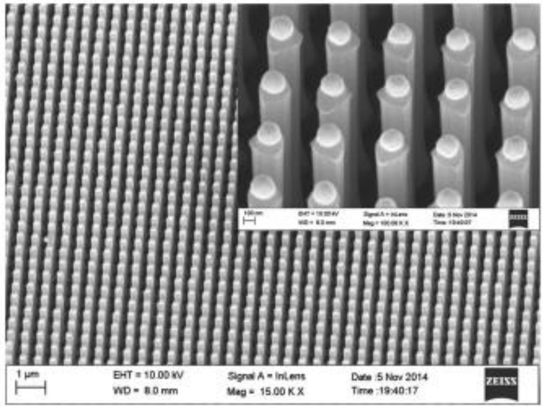
[a]The first quantity outside the brackets is normalized to the substrate area. The second quantity in brackets is normalized to the wire area and represents the results for perfect light trapping.
[b]Reference 49.

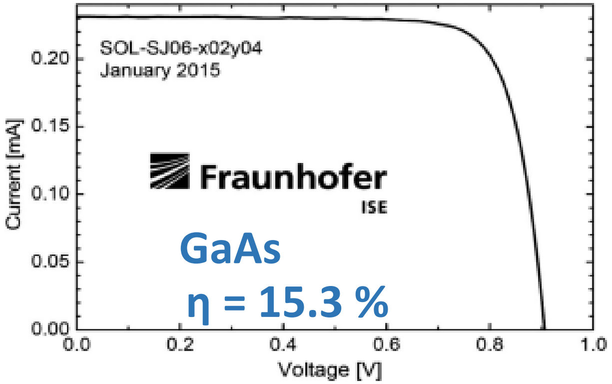
R.R.LaPierre, J. Appl. Phys. 109, 034311 (2011)

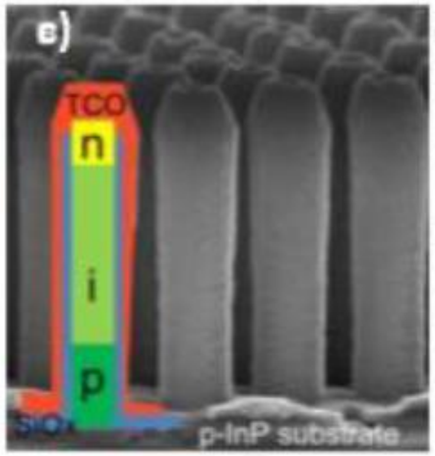
"The J-V characteristic of a nanowire diode is the result of a complicated interplay between geometry, contact method, doping concentrations, SRV, surface trap density, and thin film effects. The variation in Voc with nanowire diameter and change in Jsc with tip length indicates the importance of a monodisperse distribution in nanowire dimensions."

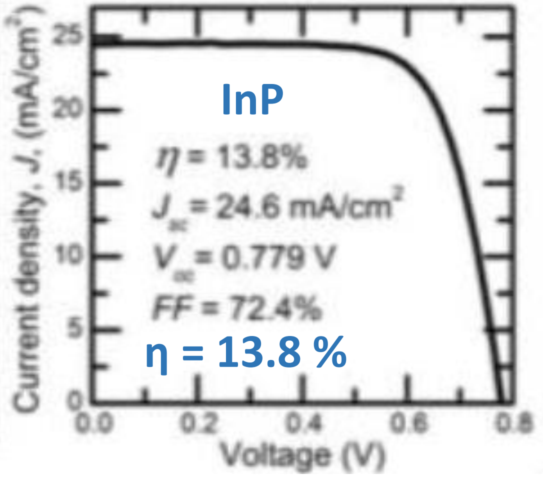
Nanowires-based Solar cells (2)

Single junction Solar Cells (axial)

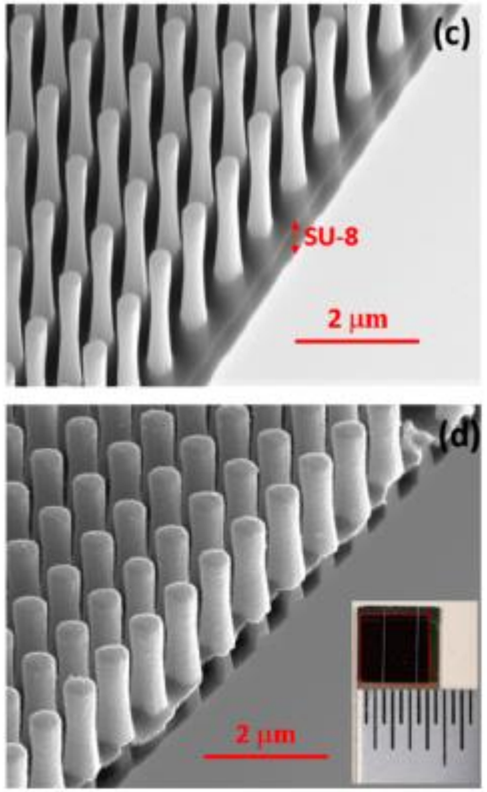


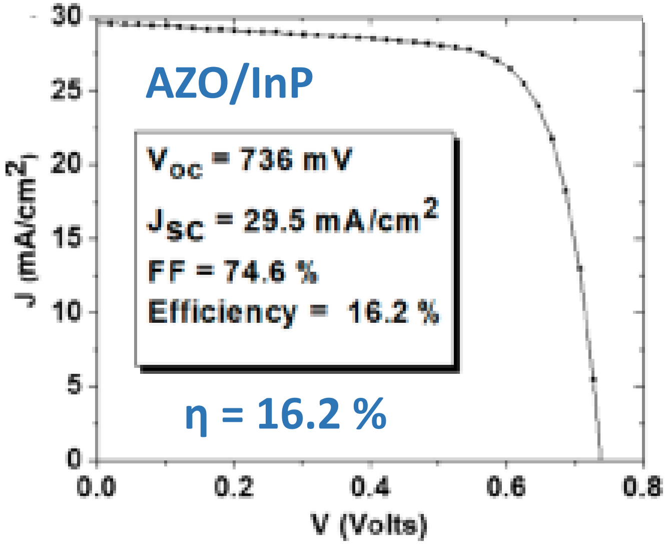






Single junction Solar Cells (radial)





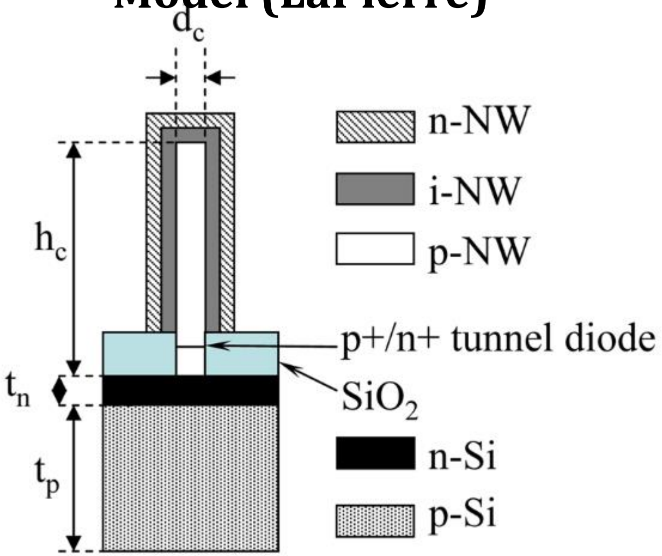
Aberg I. et al, IEEE J. OF Photov., 6 (1) (2016)

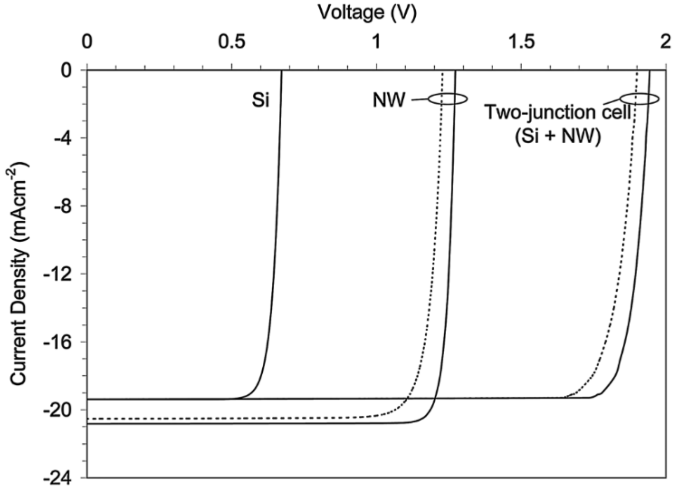
Wallentin J et al., Science, 339(2013)1057-1060.

Raj V. et al: ACS Nano, 13, 12015−12023 (2019)

Nanowire Tandem Solar Cells

Model (LaPierre)



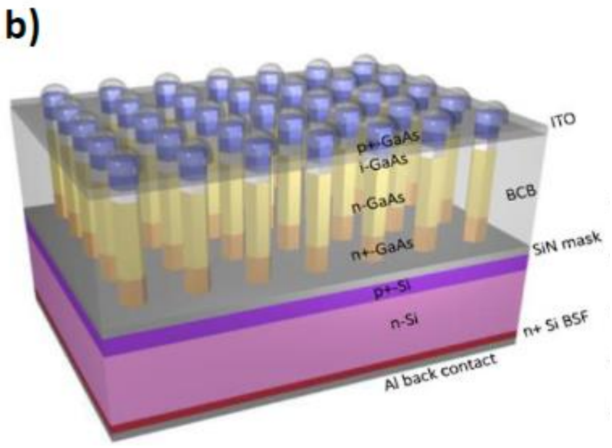


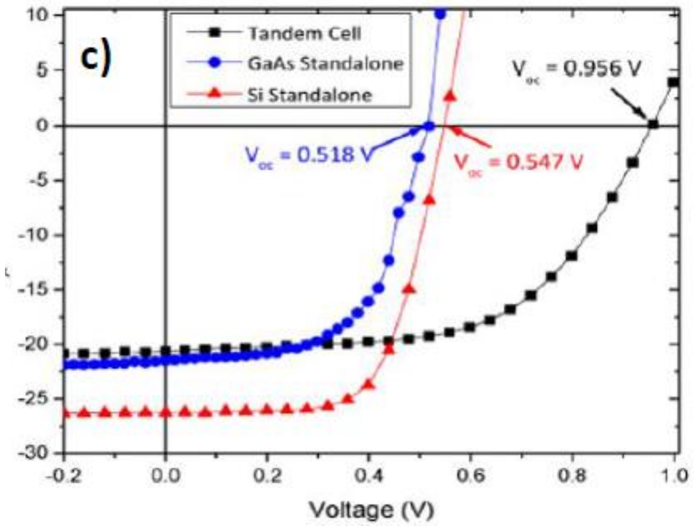
η = 34 %
(1 Sun)

η = 43 %
(x500 Suns)

LaPierre R. R., J. Appl. Phys. 110, 014310 (2011)

III-V/Si Tandem Solar Cell

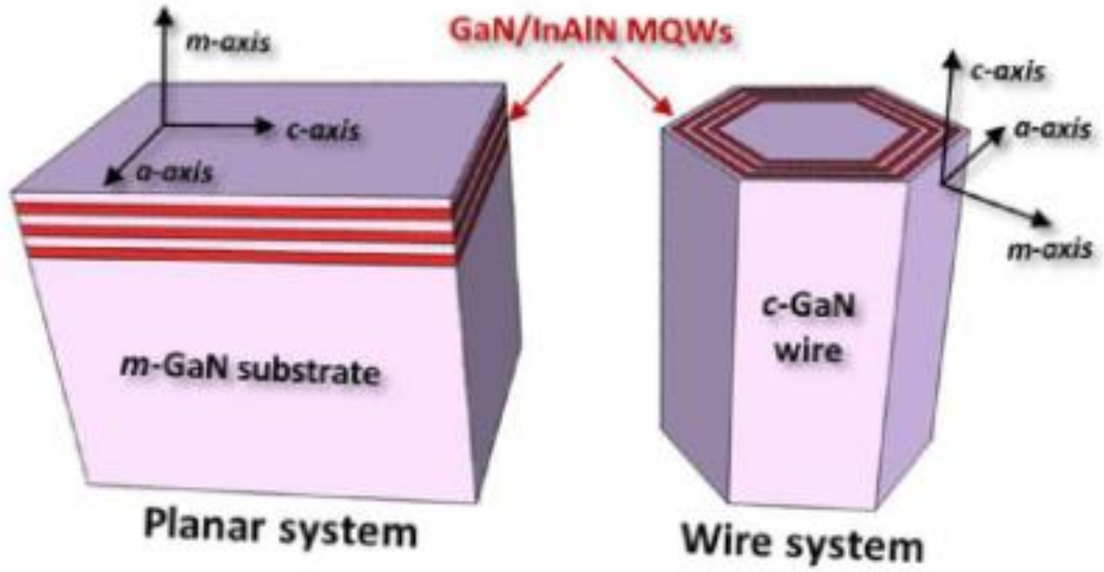


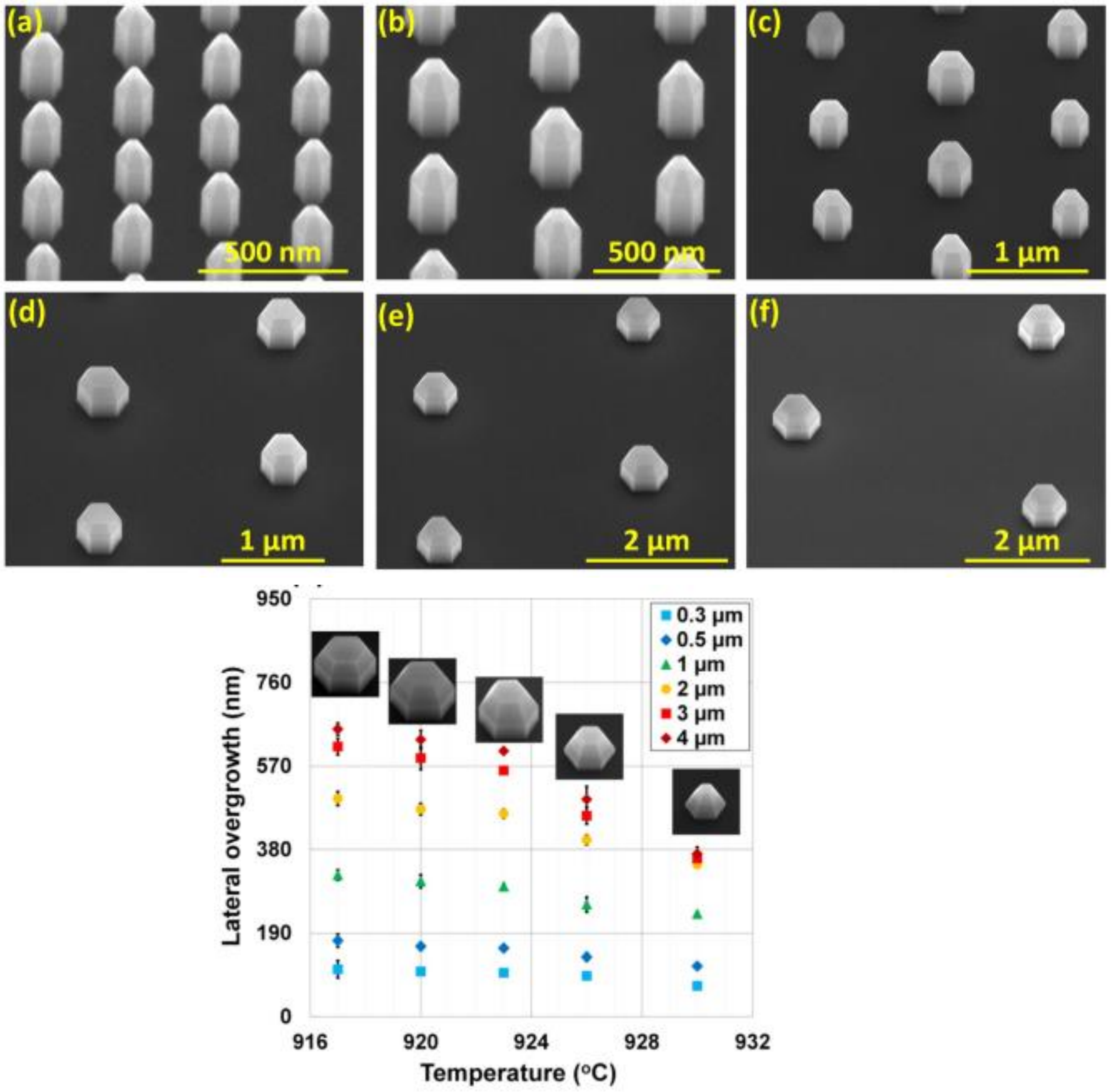


η = 11.4 %
(1 Sun)

Yao M. et al., Nano Lett. 15, (2015)

Nanowire LEDs

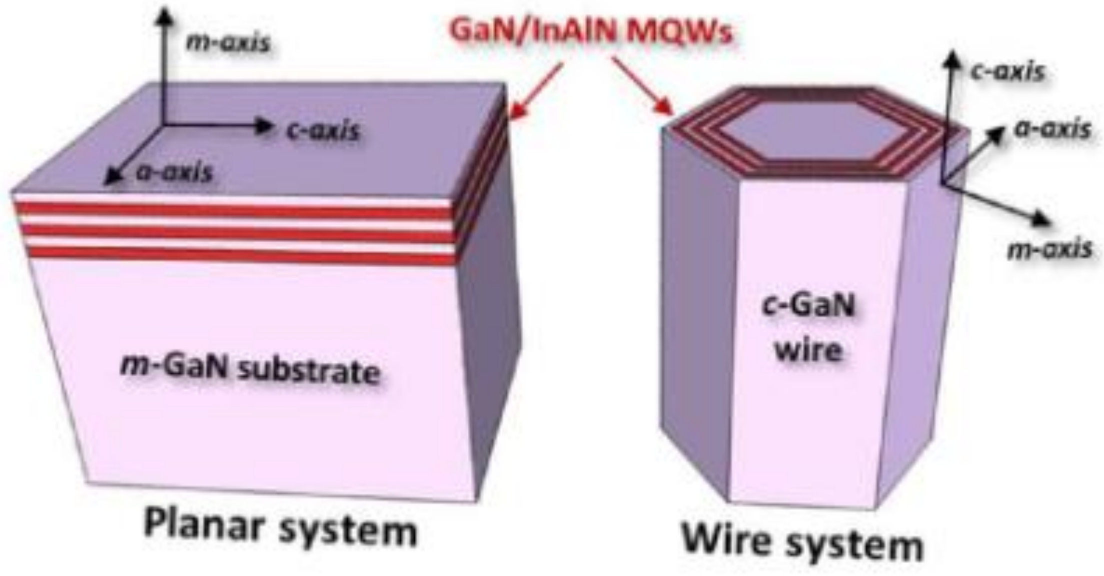


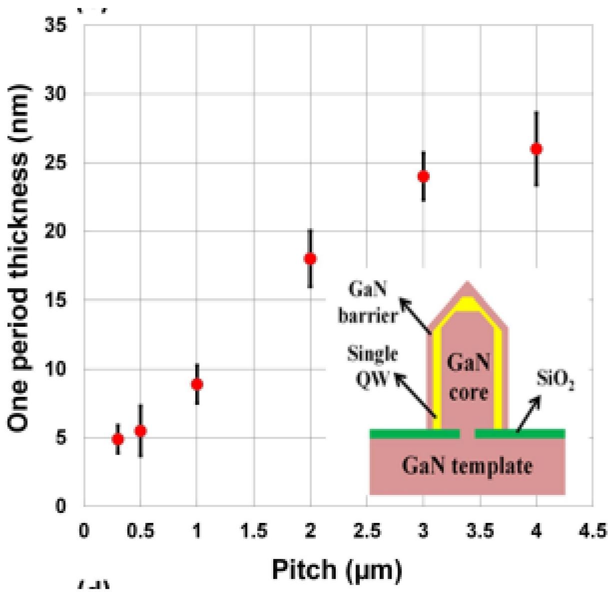


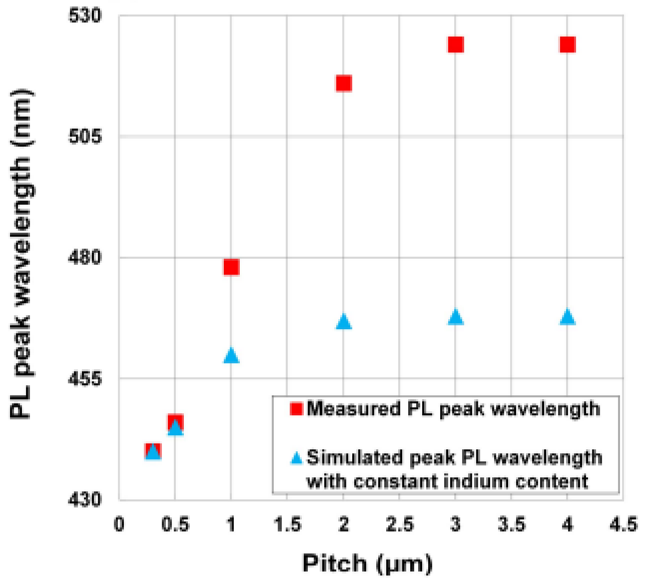
Durand C., ACS Photonics, 1, 1, 38–46 (2014)

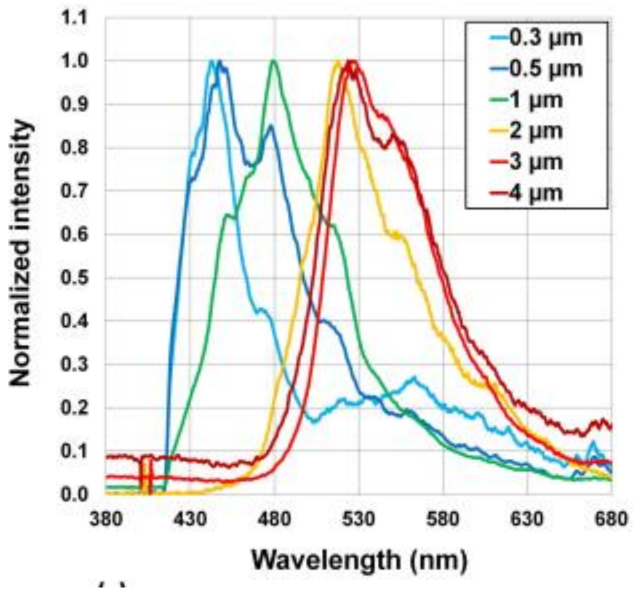
Nami M.et al Nanotechnology 28 (2017)

Nanowire LEDs





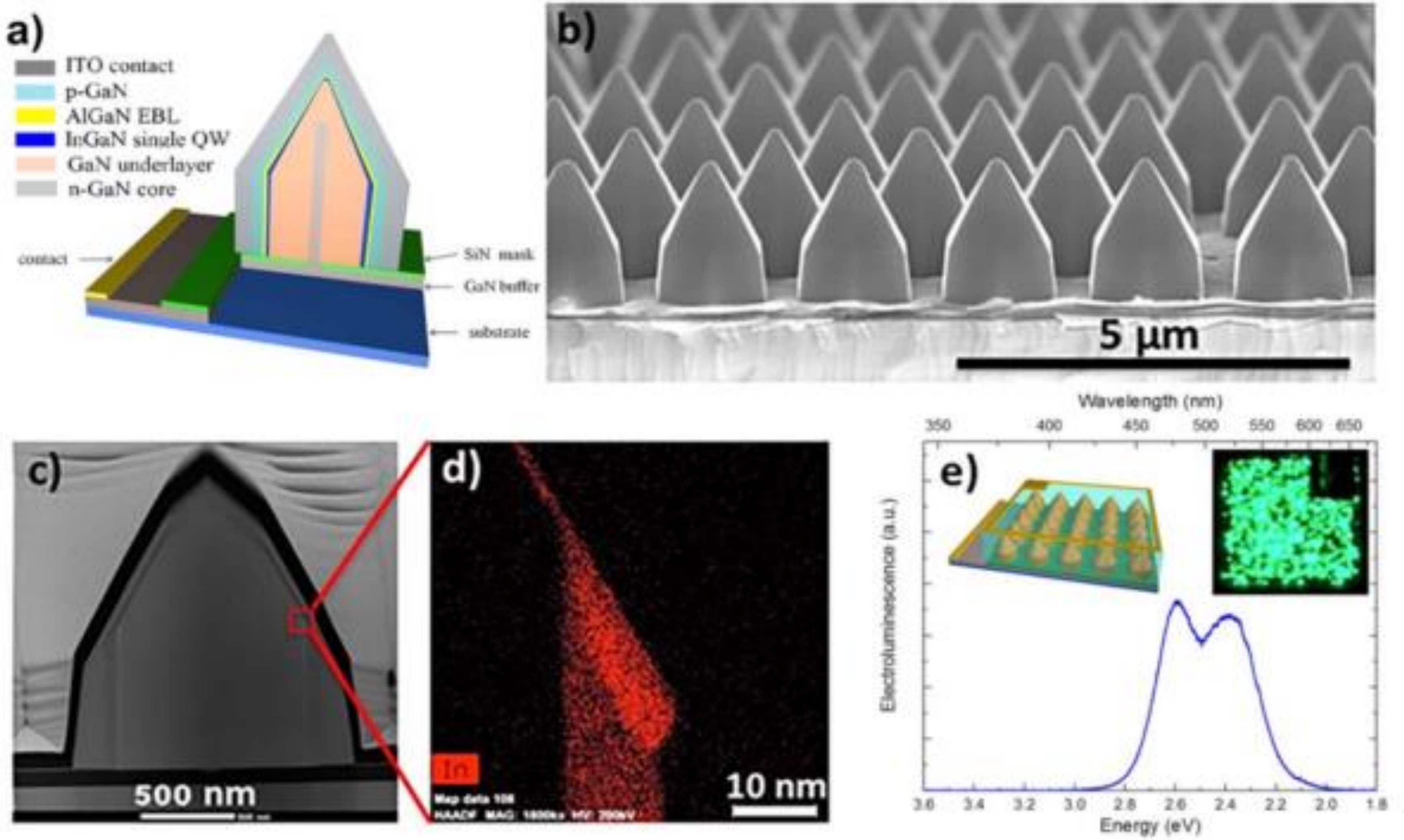




Durand C., ACS Photonics, 1, 1, 38–46 (2014)

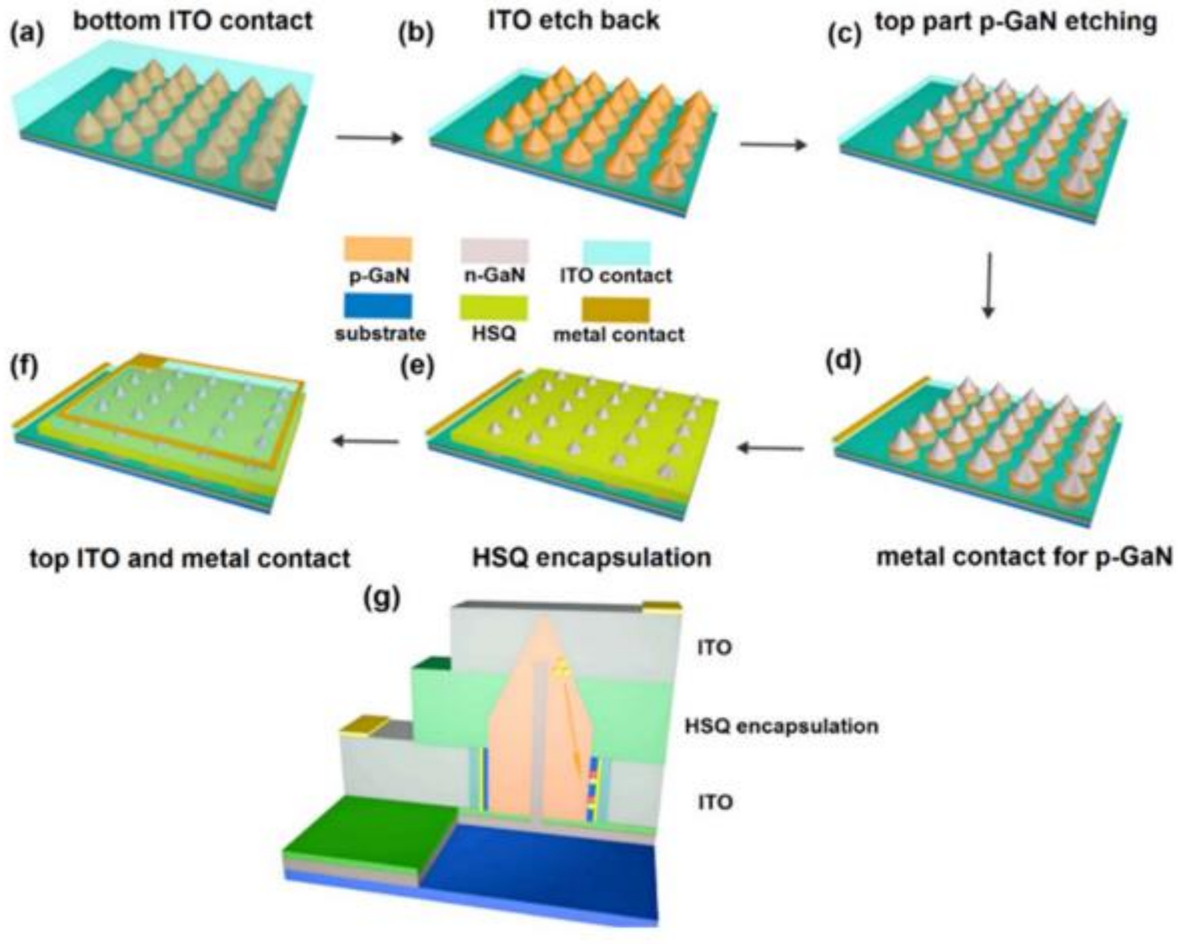
Nami M. et al., Nanotechnology 28 (2017)

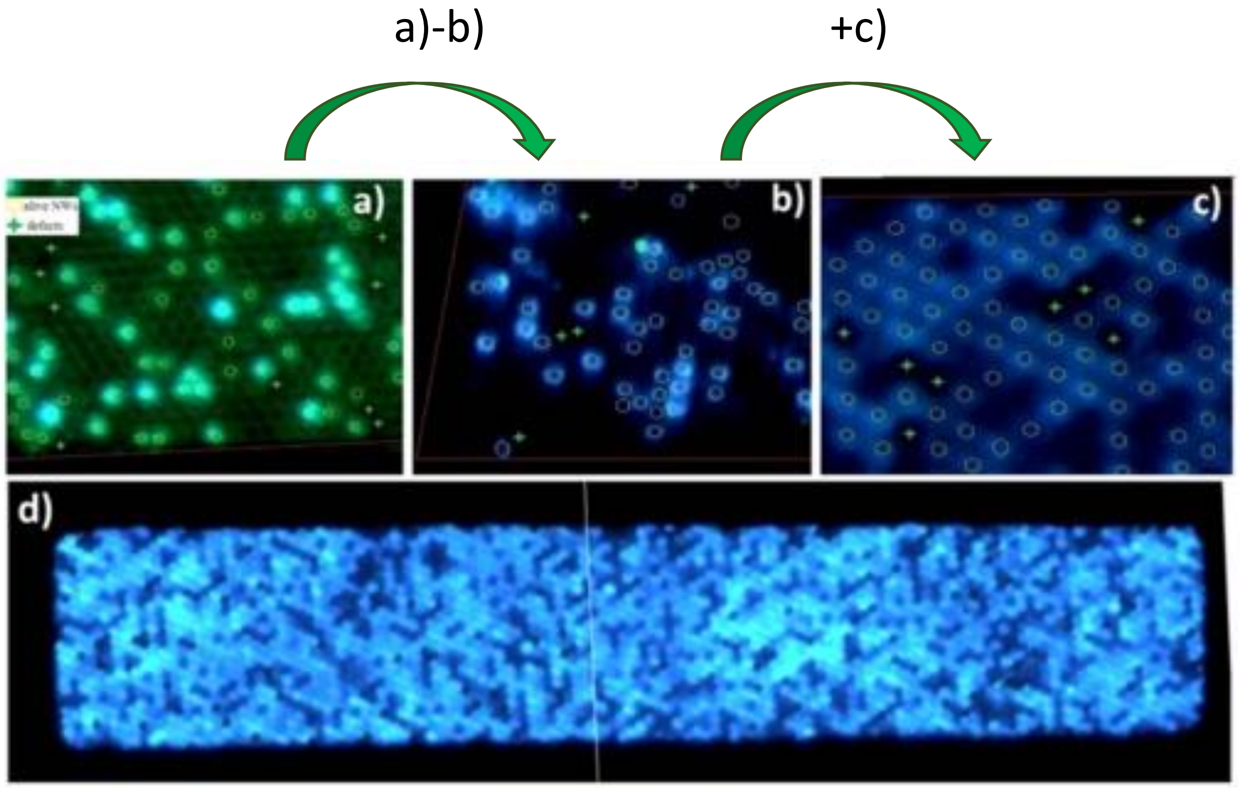
Localized In accumulation



Zhang H. et al., Nanotechnology 32 (2021)

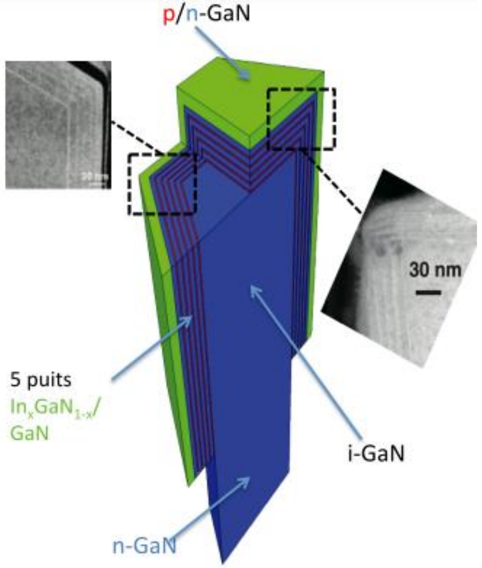
Localized In accumulation

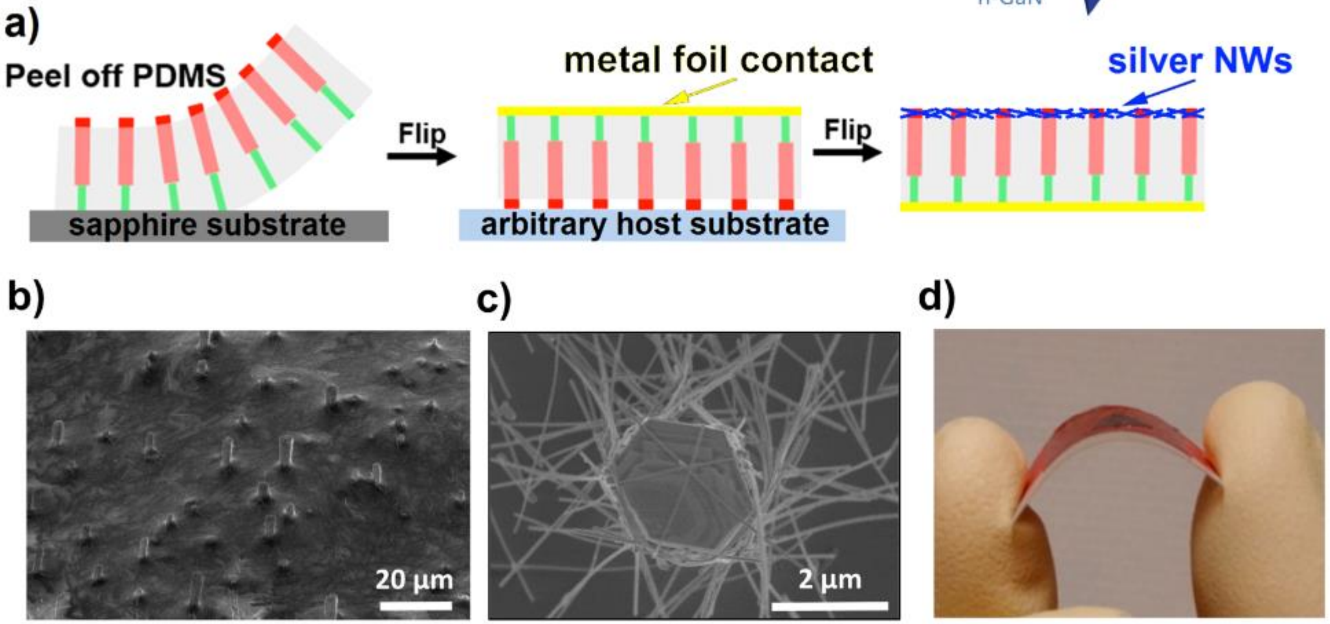


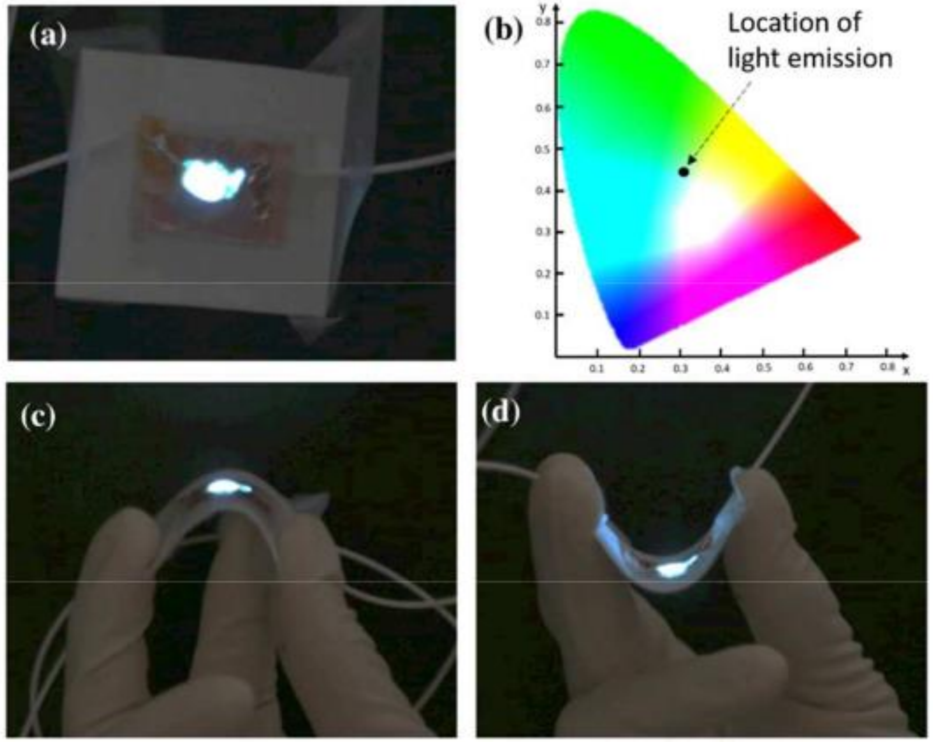


Zhang H. et al., Nanotechnology 32 (2021)

Flexible LEDs



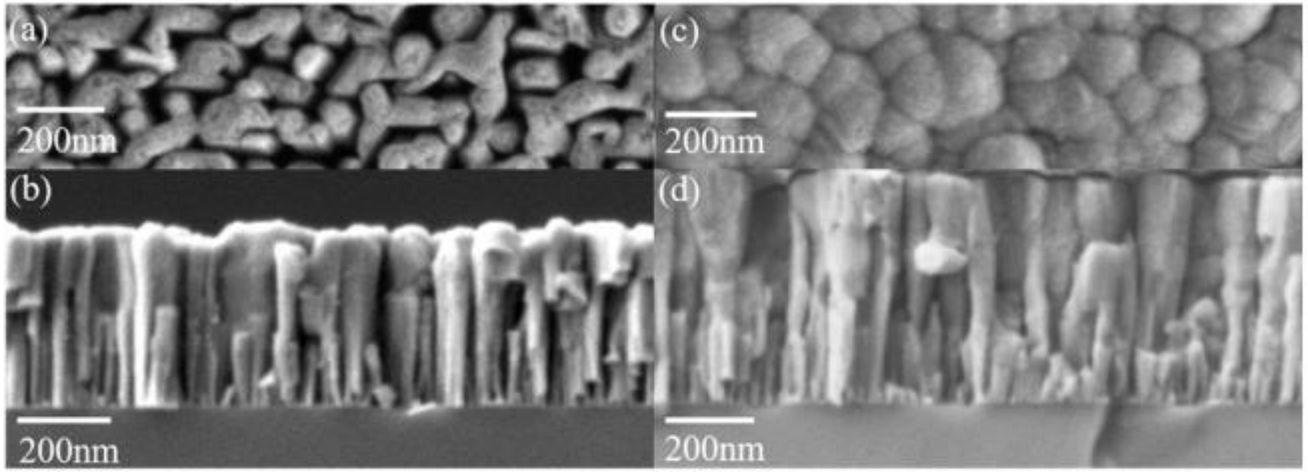


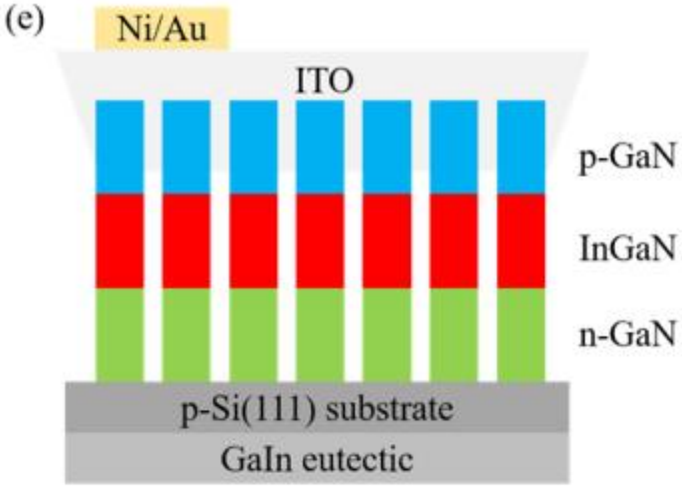


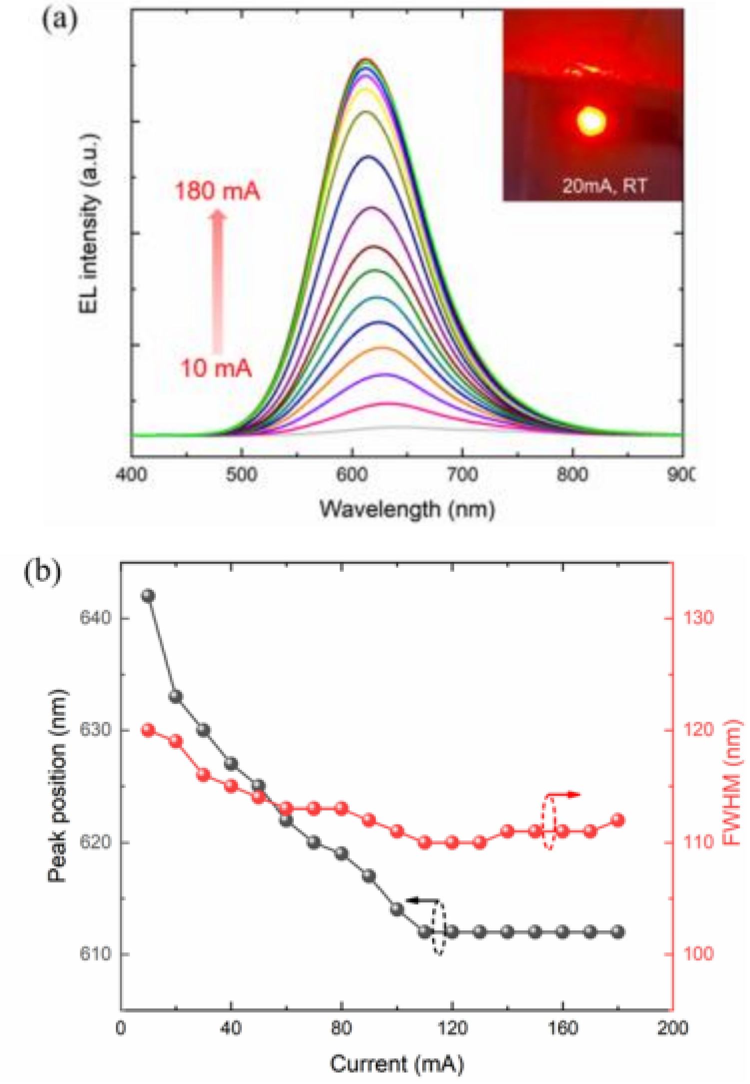
Zhang H. et al., ACS Applied Materials & Interfaces 8(39) (2016)

Guan N. et al., ACS Photonics 3(4) (2016)

High Wavelength LEDs

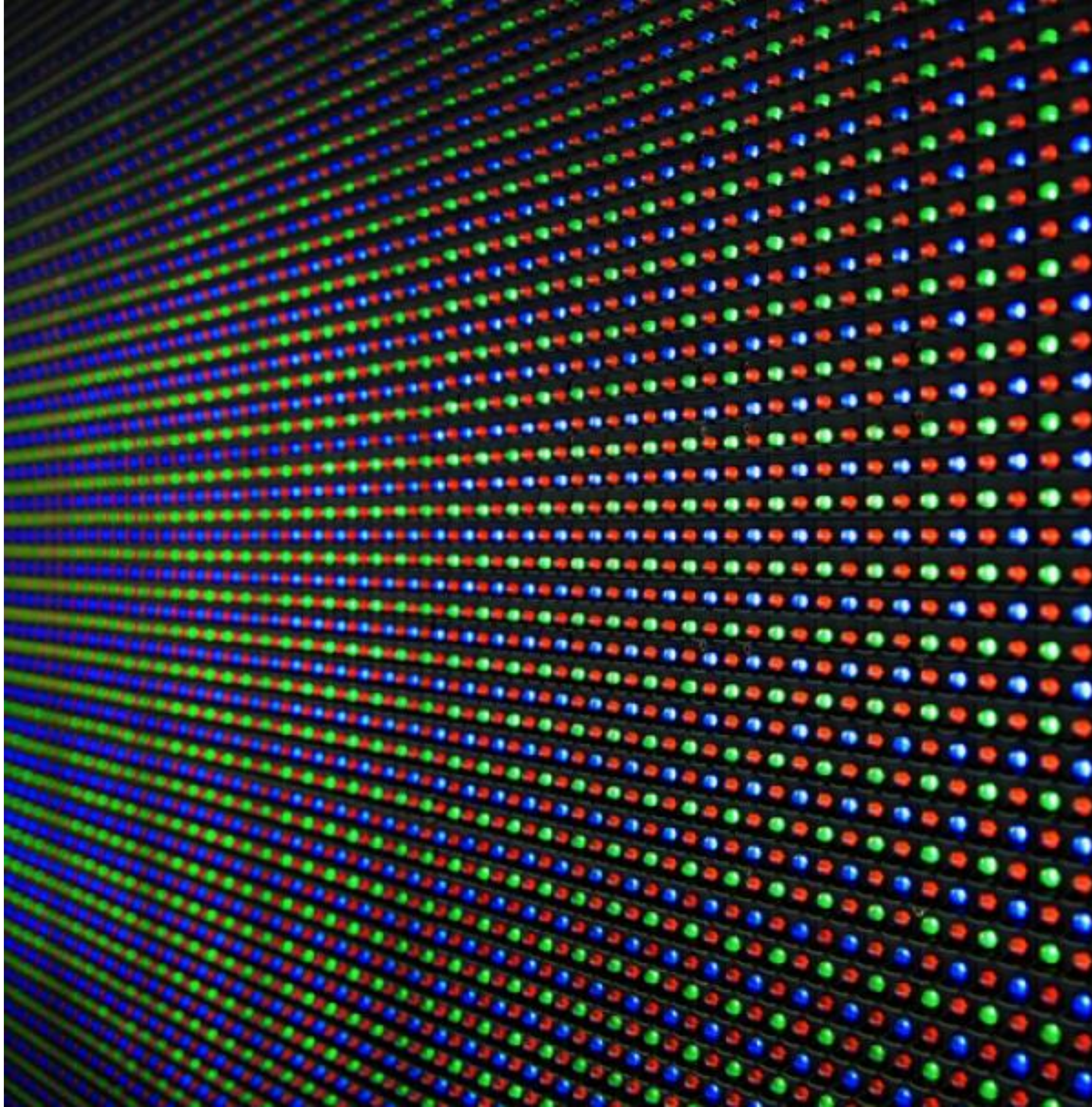






Pan X et al., Opt. Express 31, (2023)

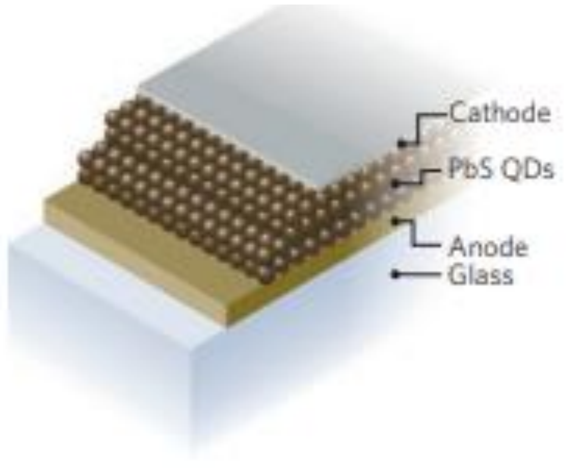
0D nanostructures
or
Quantum Dots



https://www.asianscientist.com/2018/02/tech/quantum-dot-led-metal-nanostructure/

Low dimensional solar cells

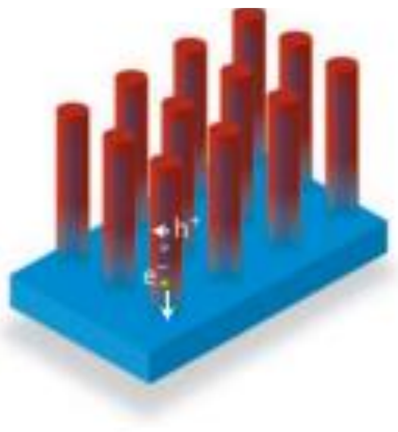
Quantum Dot Solar Cell



Benefits
Multiple exciton generation
Tunable bandgap
Low-temperature fabrication

Challenges
Charge/energy transport through QD array → No continuity
Monodispersity of QDs → QDs distribution
QD long-term stability

Nanowire Solar Cell



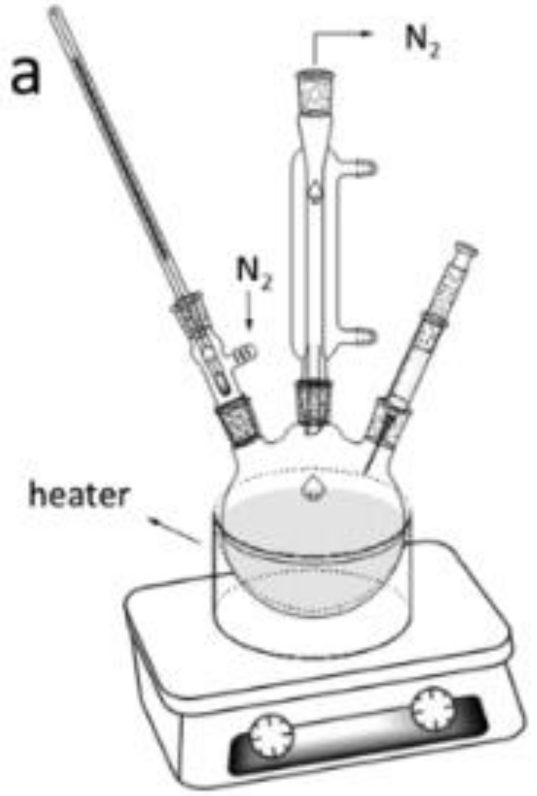
Benefits
Reduction in minority-carrier lifetime
Reduced material usage
Reduced reflectivity

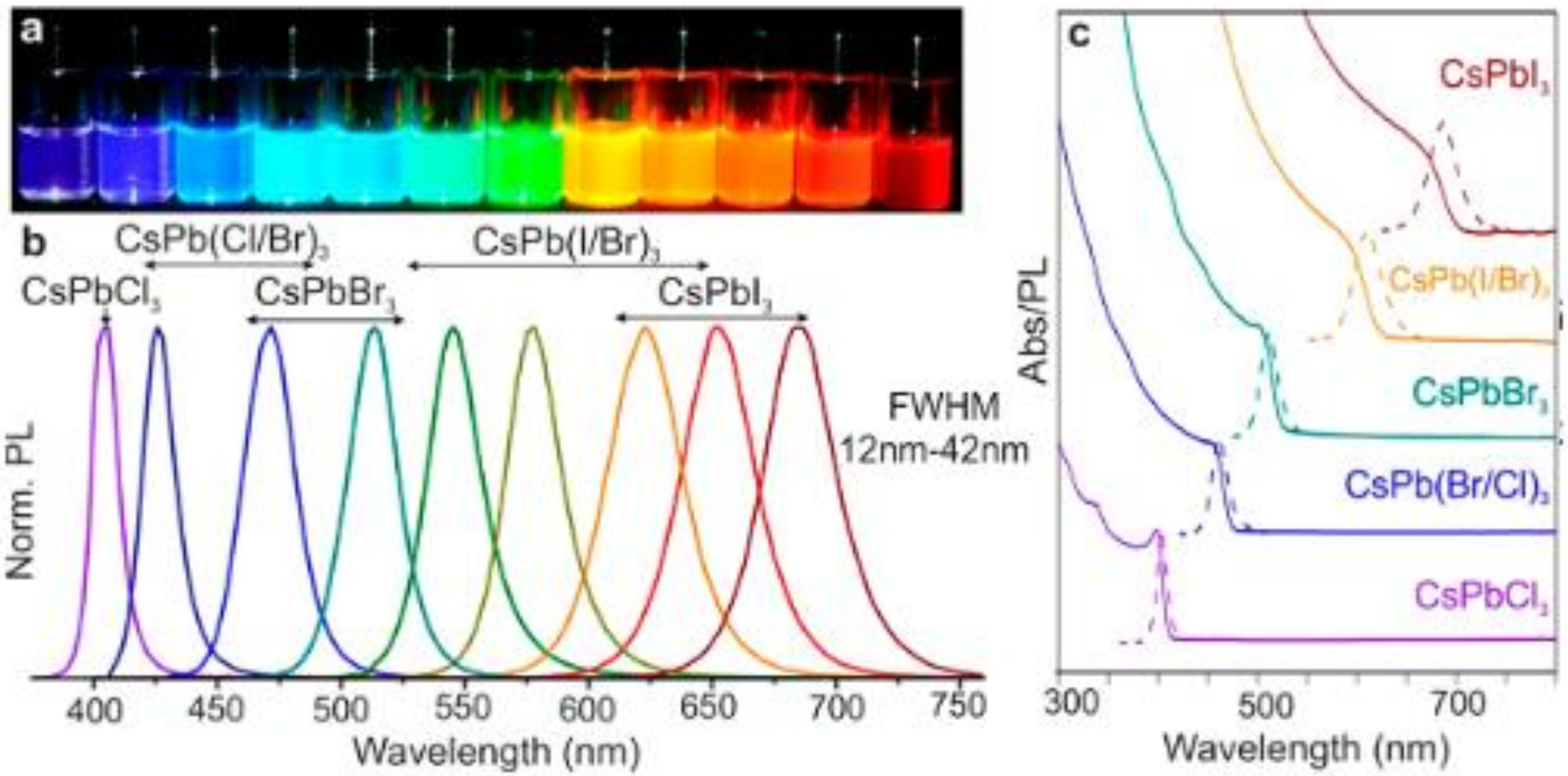
Challenges
Positional stability of dopants
Achieving high areal density
Top contact

Beard, M., Luther, J. & Nozik, A. The promise and challenge of nanostructured solar cells. Nature Nanotech 9, 951–954 (2014)

What is a Quantum Dot?

Quantum Dot - colloidal synthesis

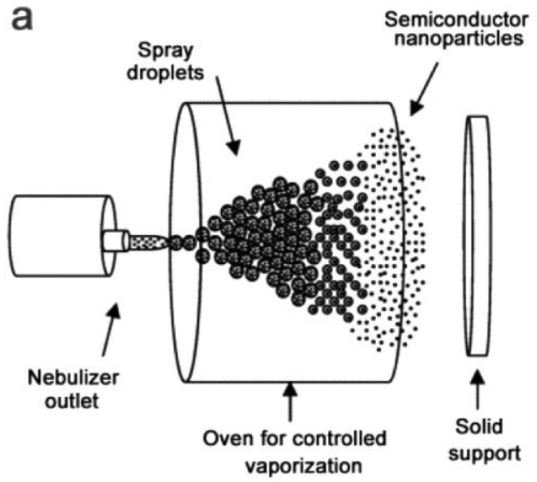


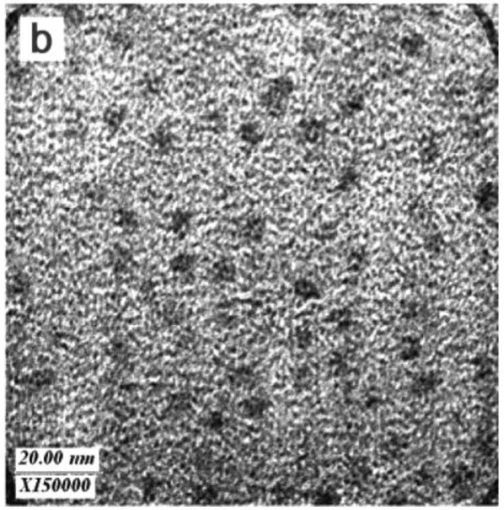


Pu Y. et al., Ind. Eng. Chem. Res., 57, (2018)

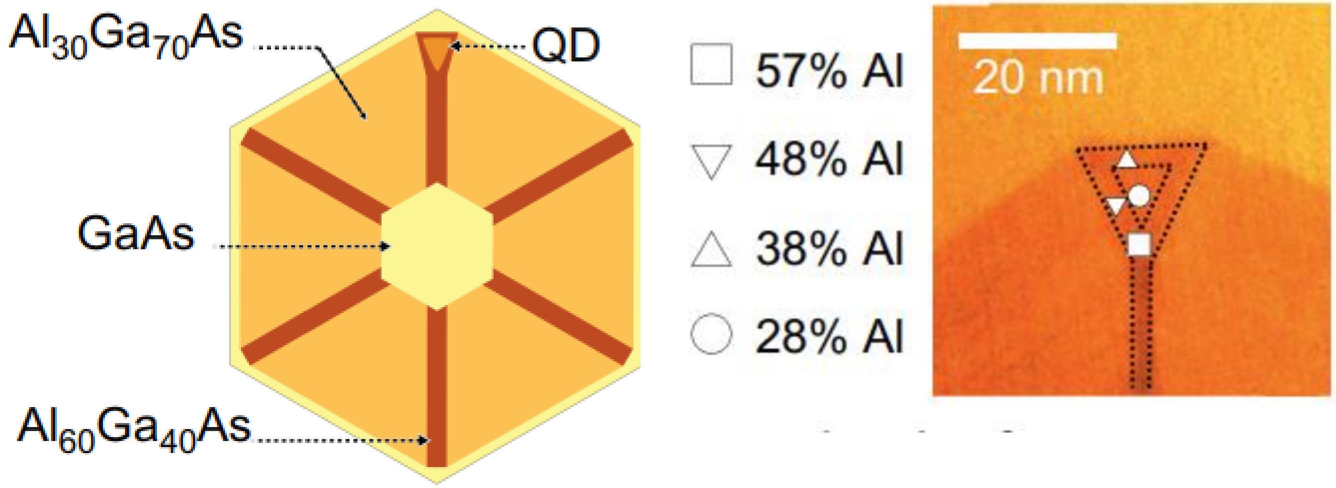
Quantum Dot - other syntheses

Spray method

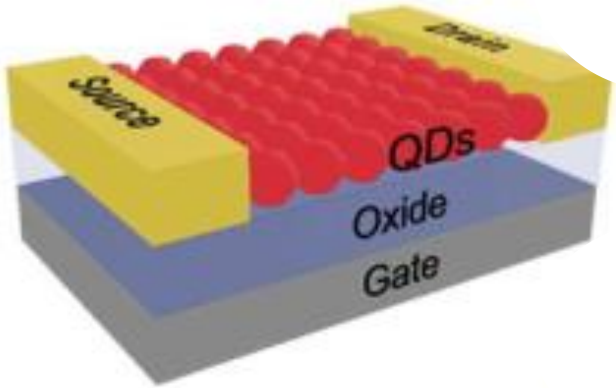




Epitaxial method

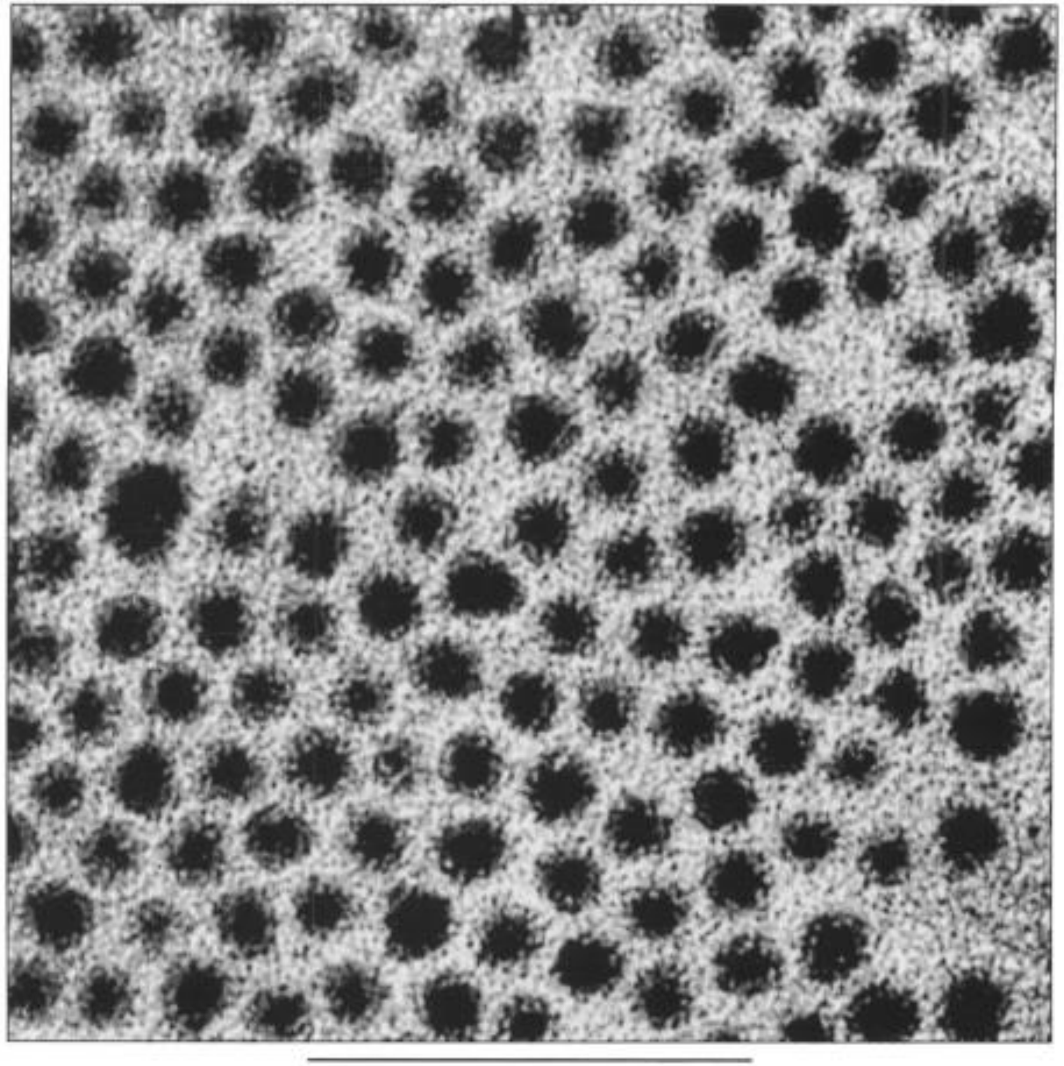


Electrostatically defined



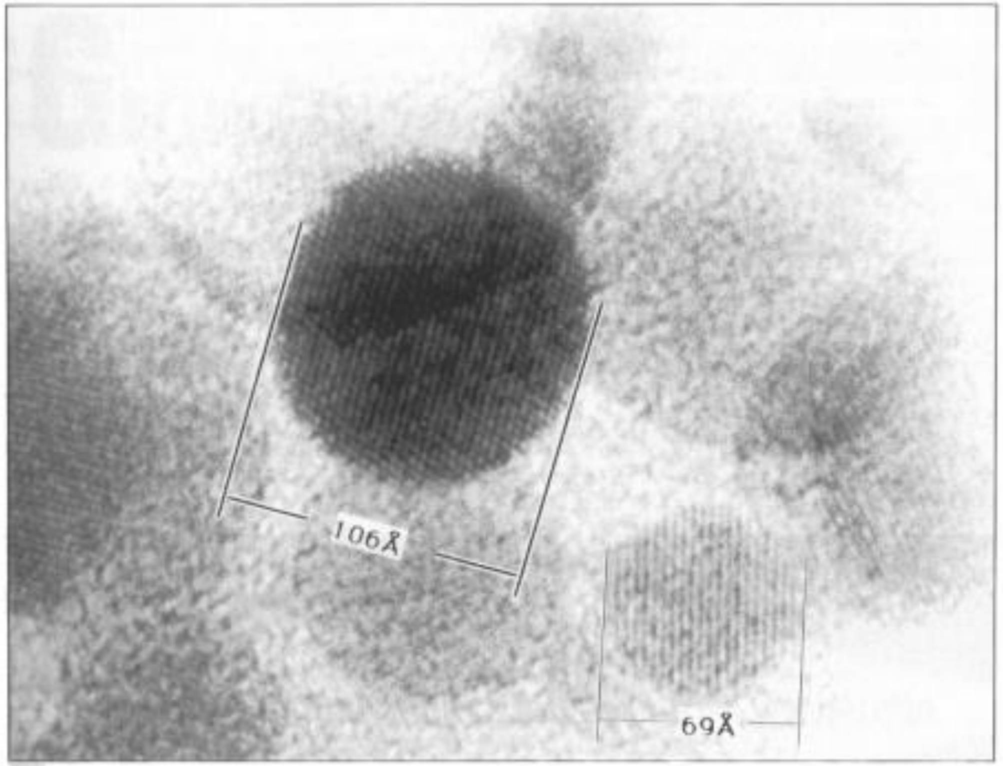
Bayer M., Ann. Phys.(Berlin) 531, (2019)
Pu Y. et al., Ind. Eng. Chem. Res., 57, (2018)

Quantum Dot distributions



InP QDs

GaAs QDs

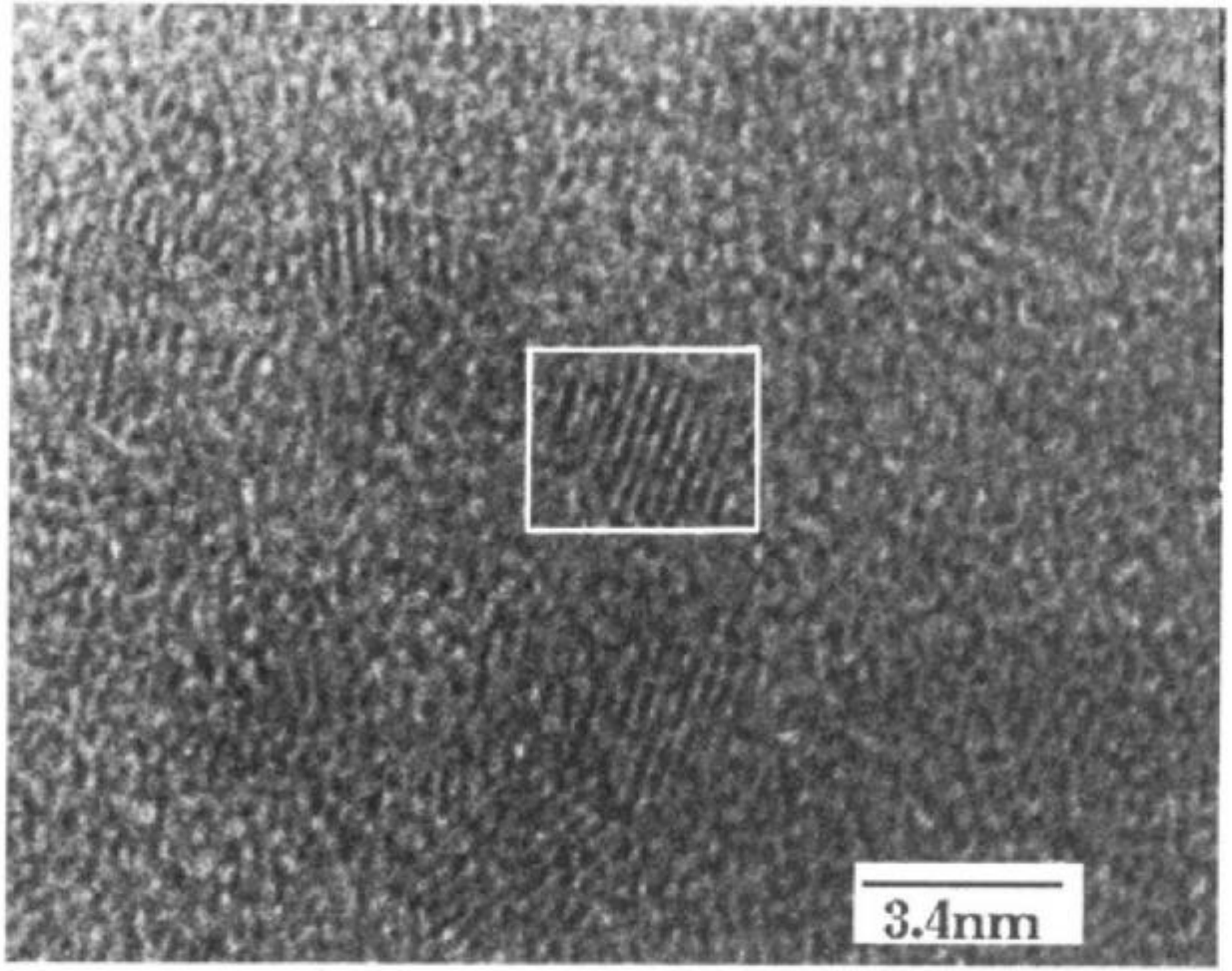


Diameter between 2 and 10 nm

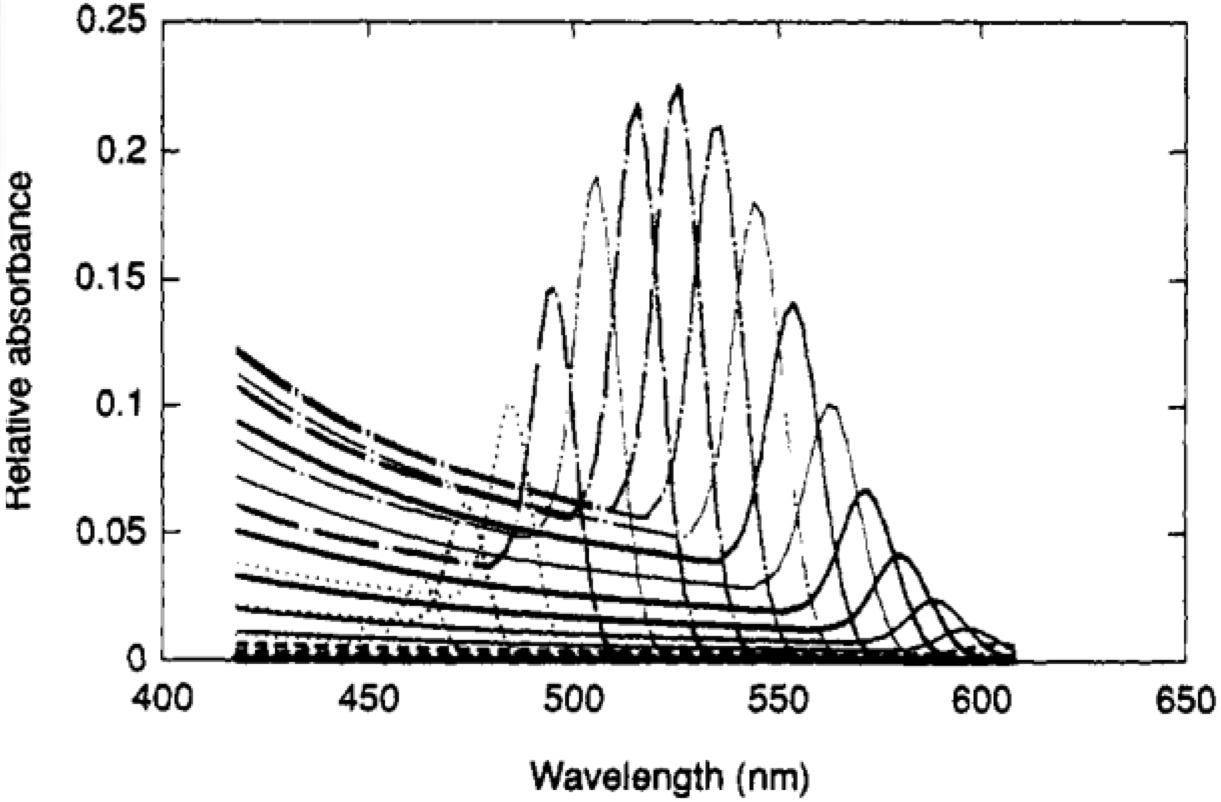
Nozik et al., MRS Bulletin, (1998)

Quantum Dot distributions

InP QDs

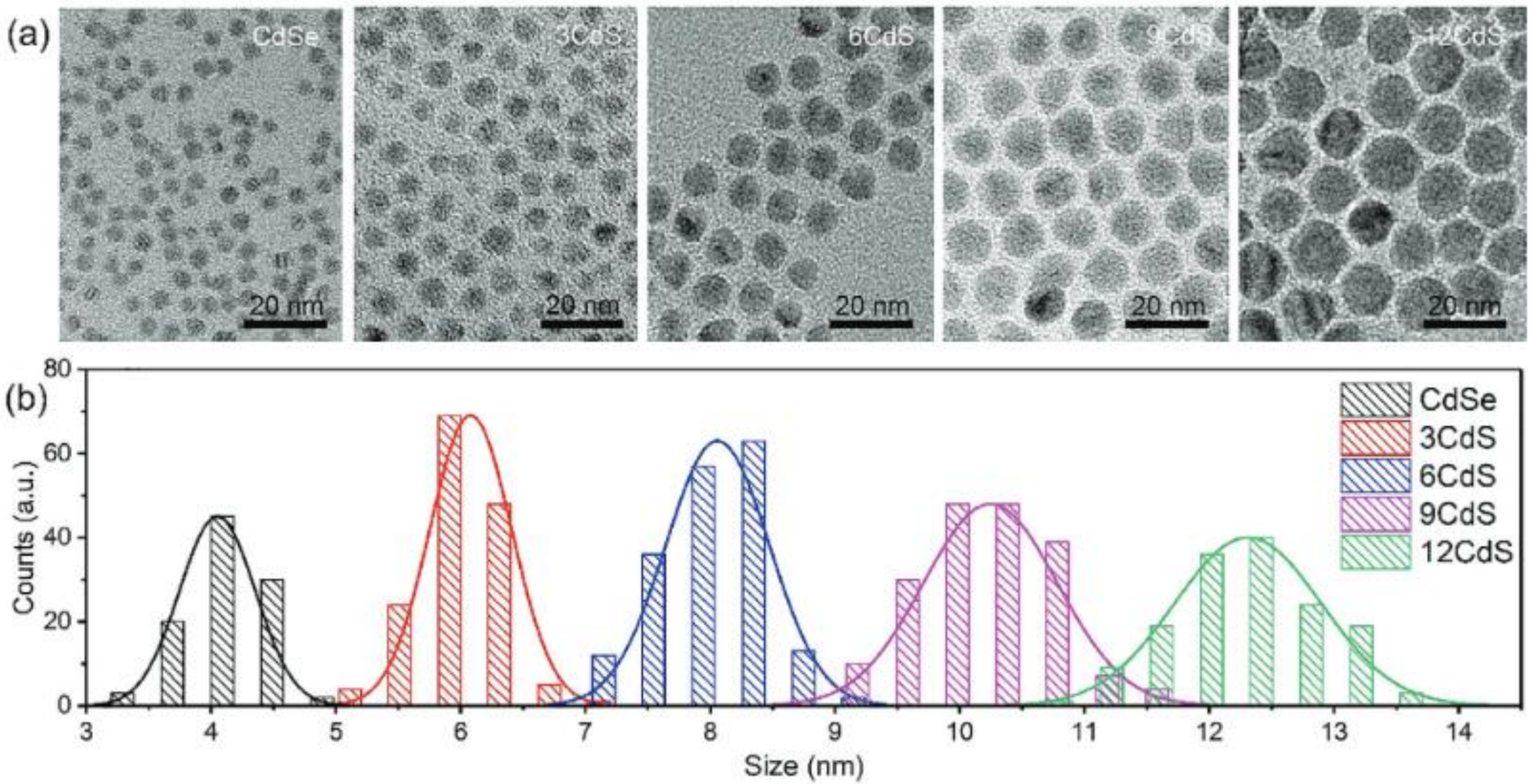


Micic et al., J. of Physical Chemistry, 98(19) (1994)



Diameter between 20 and 35 nm

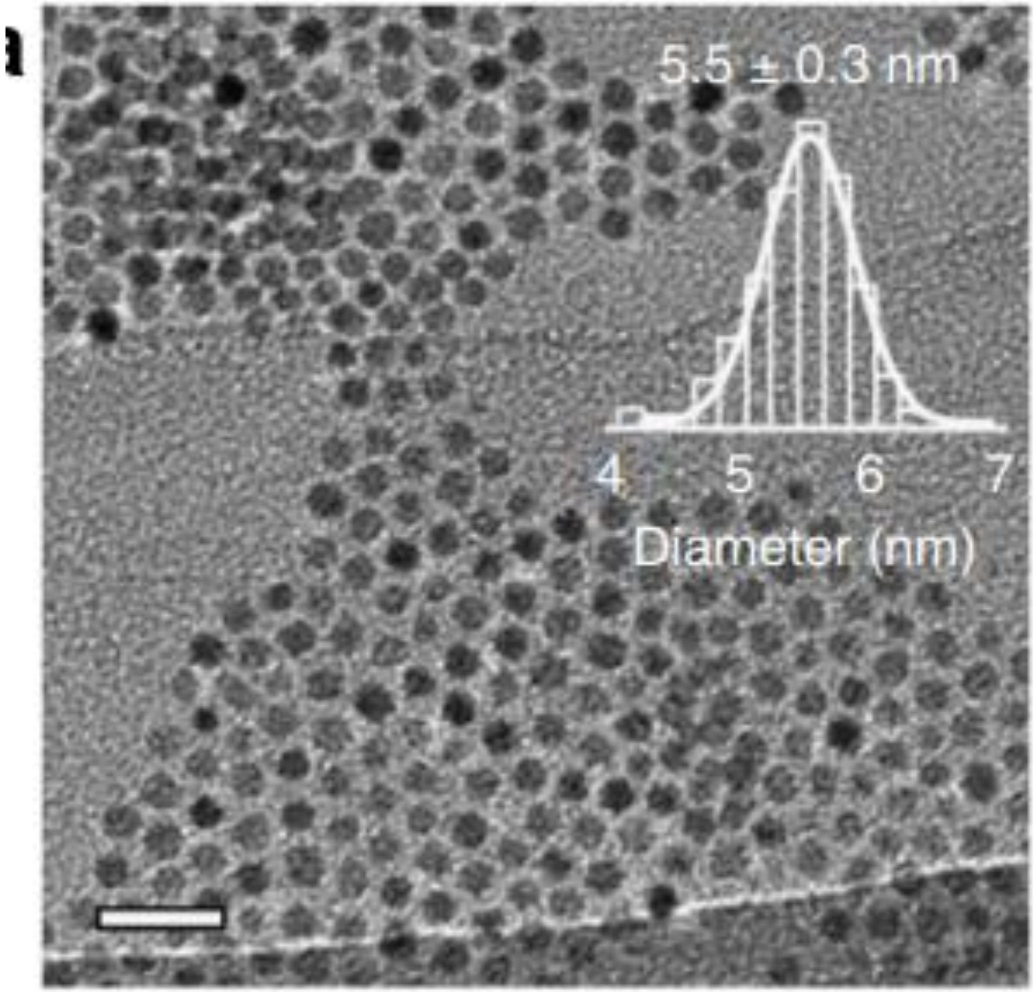
Quantum Dot polydispersion

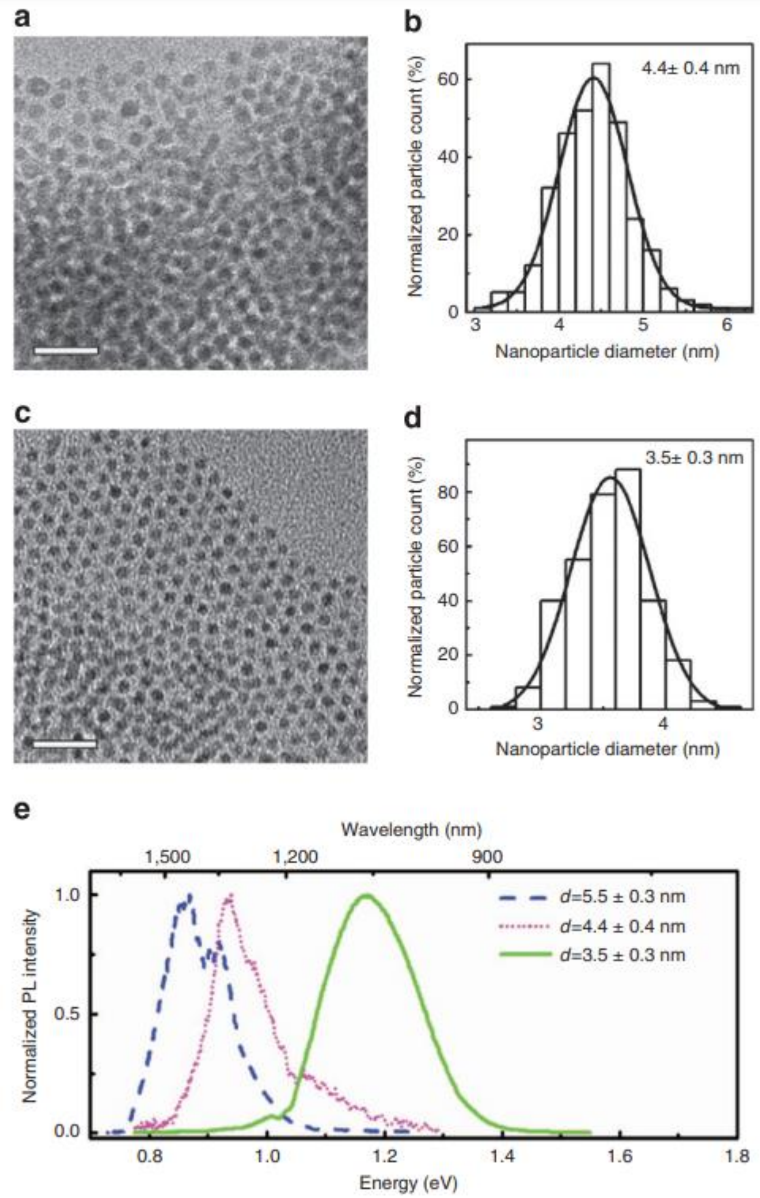


CdS/CdSe QDs

Liu G. et al., Adv. Sci. ,8, 2102784 (2021)

Quantum Dot monodispersion





PbS QDs

Yang J.et al., Nat Commun 4, 1695 (2013)

Quantum Dot – Nobel prize

The Nobel Prize in Chemistry 2023 - Quantum dots

Department of Physics < News

Moungi G. Bawendi, Louis E. Brus and Alexei I. Ekimov were awarded the Nobel Prize in Chemistry 2023 for the discovery and development of quantum dots. These tiny quantum systems have unique properties and many applications: they emit light used in television screens and LED lamps, they catalyse chemical reactions, and their emission marks the borders of tumor tissue for a surgeon. Ana Predojević, is associate professor at Fysikum: "We use the best tools and methods available to modern science to generate quantum light, harness its unique properties, and bring it closer to real-world application."

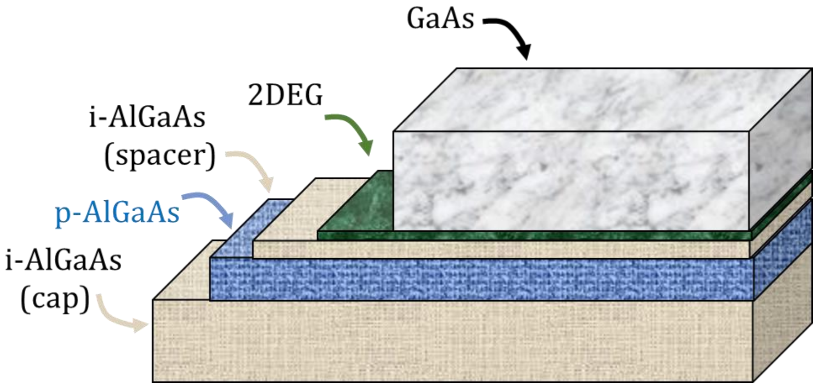
How to create a QD-LED

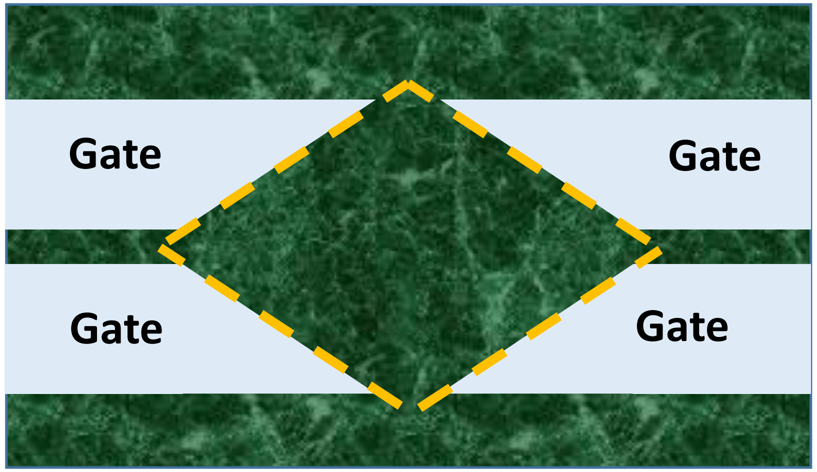
5 minutes

How to create a QD-LED

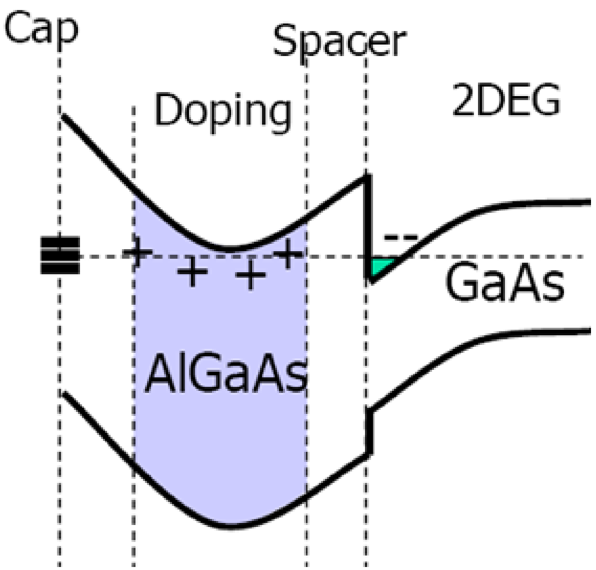
5 minutes

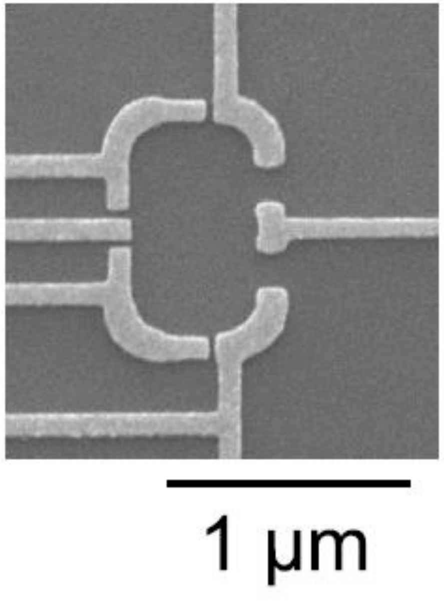
Charge transport in 0D systems

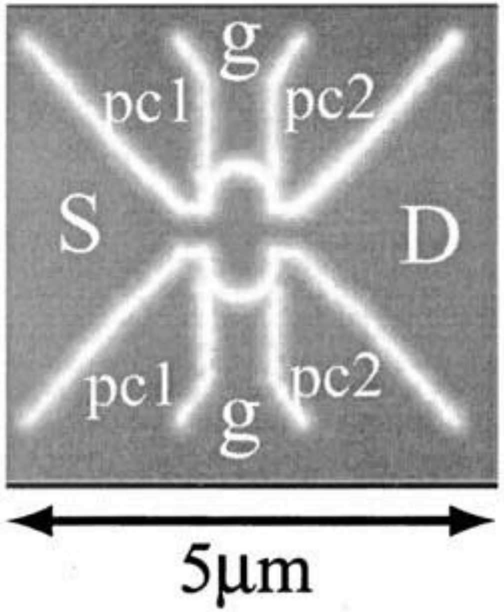




Electrostatically defined
Quantum Dot



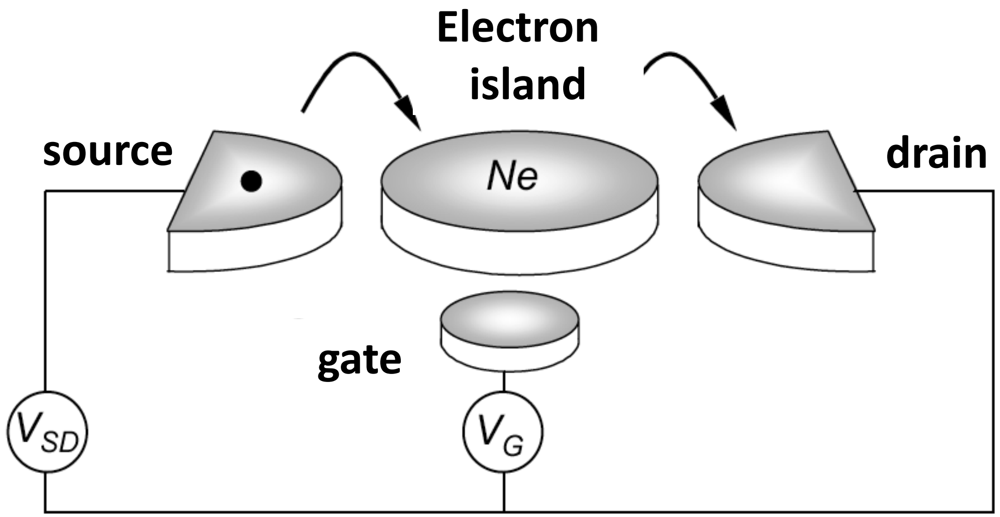




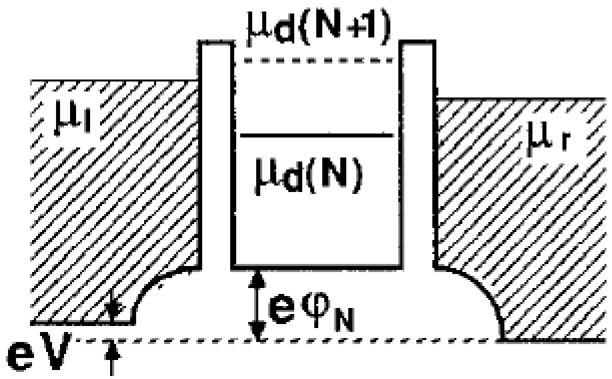
Coulomb Blockade

The controlling principle is similar to the case of the 1D channel.

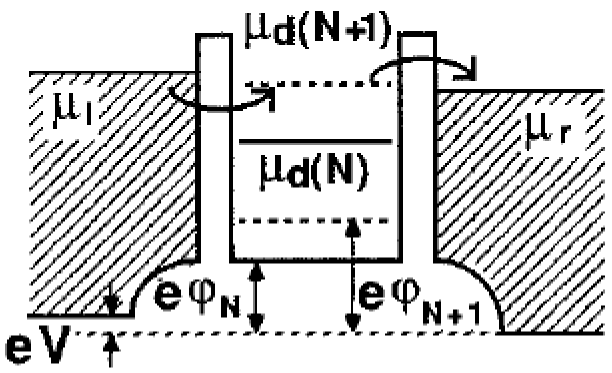
The charge transport occurs by tunnelling through an energy barrier.



Blockade



Single charge tunneling



By aligning the chemical potential of the different elements (contacts, barrier, charging potential of the QD), it is possible to control of the tunnelling by varying the gate voltage.

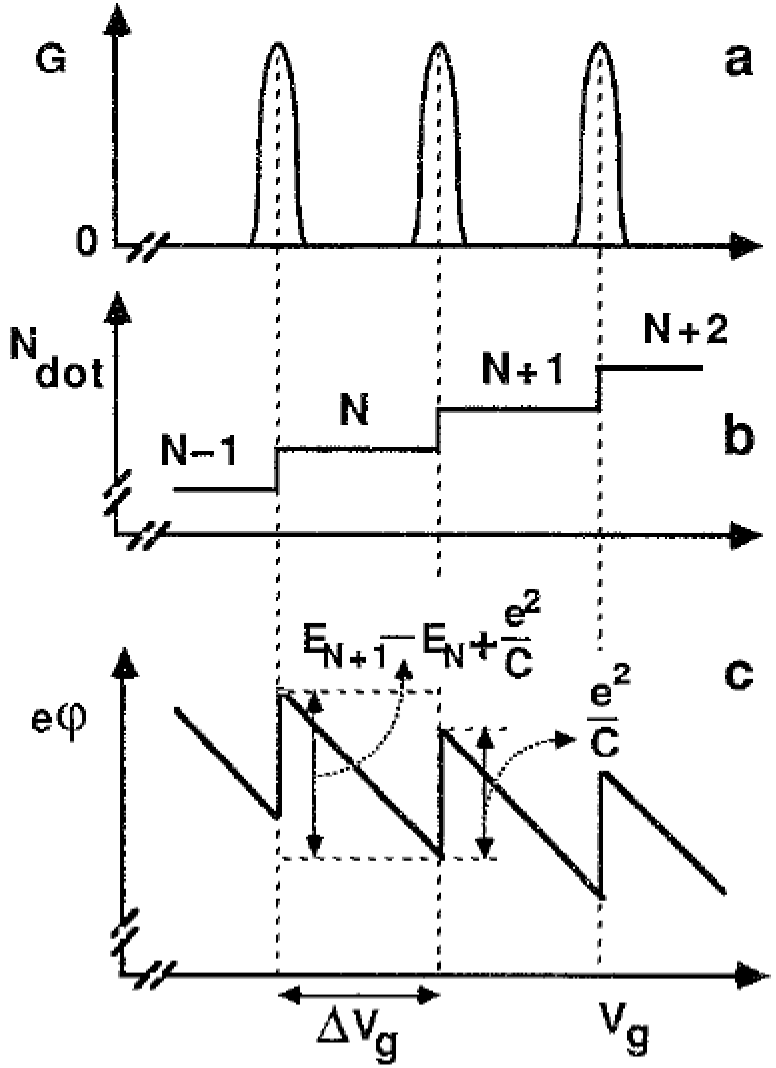
Since the energy levels available for the states in the QDs are discrete, electrons flow one-by one.

Coulomb Blockade

In the system we can observe «**Coulomb oscillations**» in the G vs V_g plot.

As the gate voltage reaches a value sufficient to enable tunnelling to an empty energy levels, electrons flows and the conductance spikes.

The energy required to «store» a single electron into the Coulomb blockade device is equal to $\frac{e^2}{2C}$, where C is the capacitance of the quantum dot with respect to the external environment.



Conductance of a Quantum Dot

How much is the quantum conductance of a Coulomb Blockade?

a. $G_0 \gg \frac{2e^2}{h}$
b. $G_0 > \frac{2e^2}{h}$
c. $G_0 = \frac{2e^2}{h}$
d. $G_0 < \frac{2e^2}{h}$
e. $G_0 \ll \frac{2e^2}{h}$

To be discussed in class