Utilizing Science & Technology and Innovation for Development

Enhanced Mid-Wave-Infrared Photo Detectors Coupled With Optical Nano-Antennas

Marriott Hotel- Amman, August 13th, 2015

Project Team

- Dr. Alaa Al-Halhouli/GJU/Jordan
- Prof. Dr. Bothina Hamad/University of Arkansas/ USA
- Prof. Dr. Omar Manasreh/University of Arkansas/USA

Brief Description

- **Growth of metallic nanoparticles and semiconductor nanocrystals.**
- **Coupling of metallic nanoparticles and optical nanoantennas to devices.**
- **Uncooled Photodetectors based on nanomaterials.**
- **Performance of photodetectors and photovoltaic devices under the influence of plasmonic effect and anti-reflection coating.**

Justifications

- Search for far-infrared (long wavelength) photodetectors that can operate at room temperature with high detectivity ($D^* \geq 10^{12}$ cm.Hz$^{1/2}$/W).
- Coupling of dissimilar materials to produce a new materials with enhanced properties.
- Coupling optical nanoantennas and metasurfaces to generate plasmonic effects, which in turn enhance the performance of the devices.
- Apply the new approaches to enhance the performance of solar cells

Objectives

- Establish a collaborative research between GJU and University of Arkansas.
- Investigate the effect of optical nanoantennas on the performance of uncooled infrared photodetectors.
- Apply the new approaches to solar cells including plasmonic effect and antireflection coatings.

Scope of work/Duration
Estimated Budget

Scope of work: The scope is grow semiconductor nanocrystals and metallic nanoparticles to fabricate photodetectors and photovoltaic devices then couple these devices to optical nanoantennas and anti-relfection coating for the purpose of enhancing the performance of the devices.

Duration: 24 months

Estimated Budget : JD 180,000

Methodology of Implementation

- Growth of semiconductor nanocrystals, such as PbSe, CdSe, InP, core/shell nanocrystls, and metallic nanoparticles.
- Fabricate infrared photodetectors and photovoltaic devices
- Deposit optical nanoantennas and metasurfaces on top of the devices to investigate plasmonic effect on the performance of the devices.
- Couple anti-reflection coating layers, grown by sol-gel method, to the devices to minimize the photons reflection from the surface of the devices.
- Investigate the above approaches to implement them for mass production of solar cells and panels.

Expected output

- Creation of easy to follow approaches to enhance the performance of infrared photodetectors and photovoltaic devices by utilizing sol gel, and colloidal growth methods.
- Implementation of the new approaches for industrial mass production of solar cells.
- Production of uncooled infrared photodetectors with enhance performance.
- Exchange of students and expertise between scientists and engineers in both Jordan and United State.
- Promote basic research activities in Jordan

Impact

- Technology transfer and the know how to universities in Jordan.
- Student training and exchanging in both Jordan and USA
- May have an impact on the solar energy industry in Jordan and enhance performance on the solar cells.
- May have impact on local and national economy.

Sustainability

- It is expected that this project will lead to the writing of other proposals in the field of detectors and solar energy such that the research in nanotechnology will be sustained for many years to come.
- This project will generate research interests in related fields, such as biosensors and MEMs sensors.
- A small business company may be established to transfer the technology from basic research to application and development that could impact the local economy.

Action Plan

Material growth: The following materials growth will be used:

- MBE growth for wafers including quantum structures and dots.
- Colloidal growth of semiconductor nanocrystals and metallic nanoparticles.
- Electron beam lithography to design optical nanoantennas and metasurfaces (resonators)
- Sol-gel methods to grow nanorods and nanotubes for antireflection coating layers.

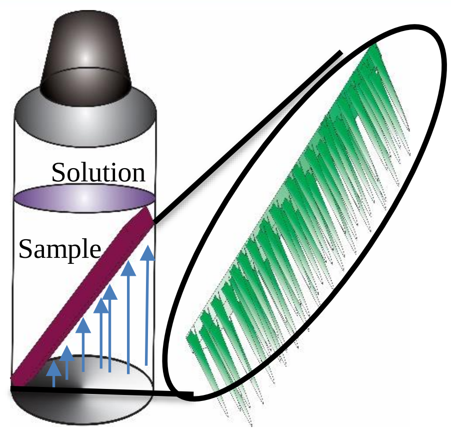
Device Fabrication: Photodetectors, photovoltaic devices (solar cells), and sensors will be fabricated using the standard chemical wet etching photolithograph as well as dry etching ICP-RIE methods.

Sol-Gel Growth of antireflection coating layers

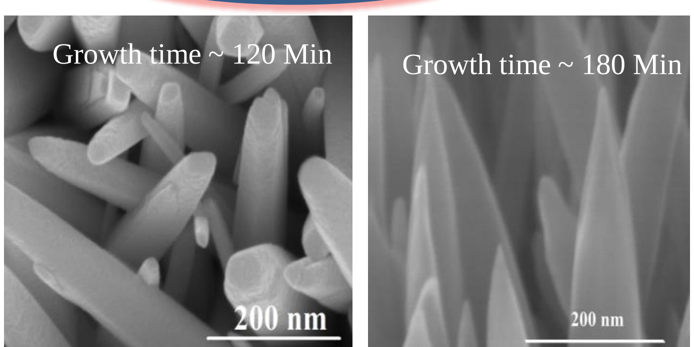
Chemical bath deposition process of zinc oxide nanoneedle for Broadband nanostructure antireflection coating

ZnO Nanoneedle growth solution

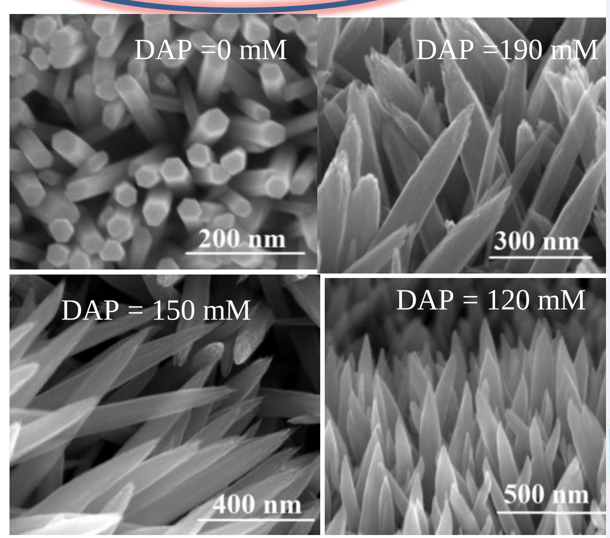
- Zinc Nitrate Hexa-hydrate → Dissolve in Water
- Hexamine → Dissolve in Water
- pH control
- Add Diaminopropane
- ZnO Nanoneedle growth solution



time control



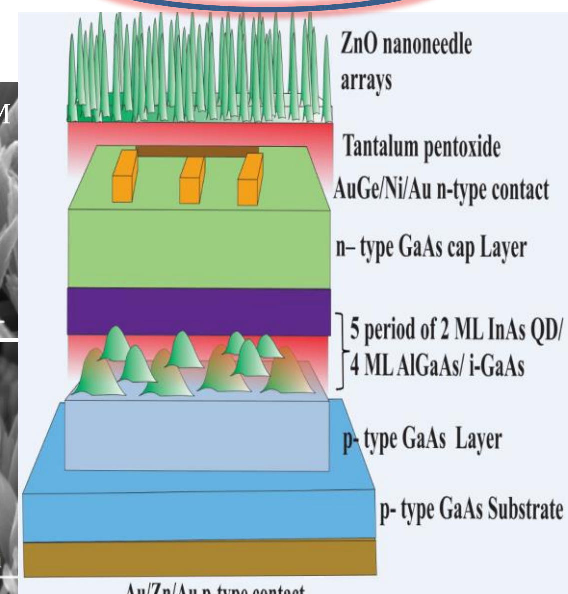
pH control



Hydrothermal Growth of Nanoneedle

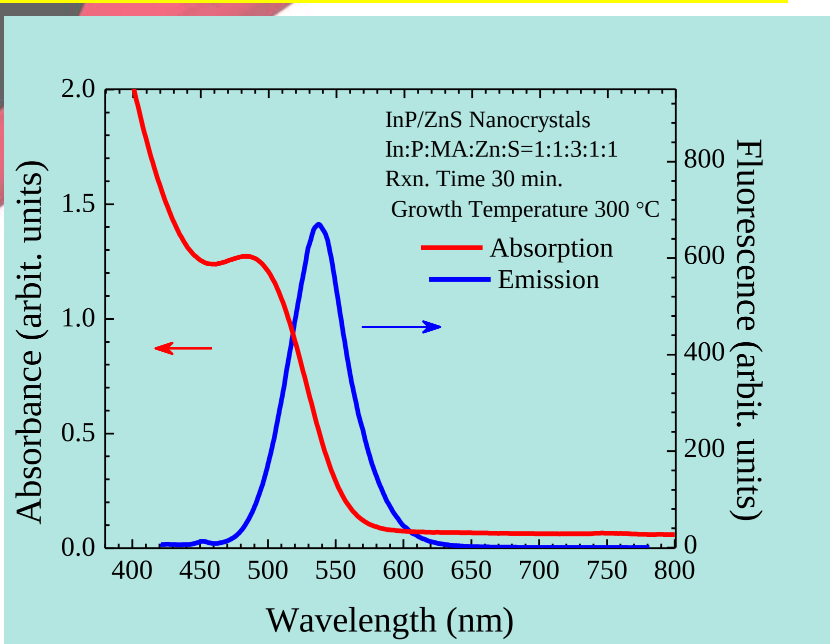
- Pristine Solar cell → (Ta_2O_5 Sol-gel spin coated) → Solar cell coated with Ta_2O_5 layer → (ZnO seed layer Spin coated) → ZnO Seed Layer deposition
- Solar cell placed upside down in the aqueous solution bath at 85 ºC → (CBD Growth of ZnO nanoneedle arrays) → Growth period of 3 hour → Solar cell was rinsed thoroughly with DI water, dried under nitrogen annealed at 150 ºC

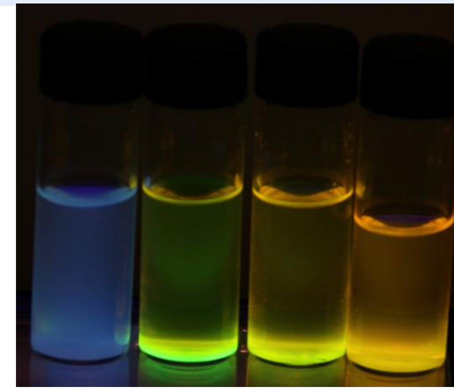
Solar cell with ARC



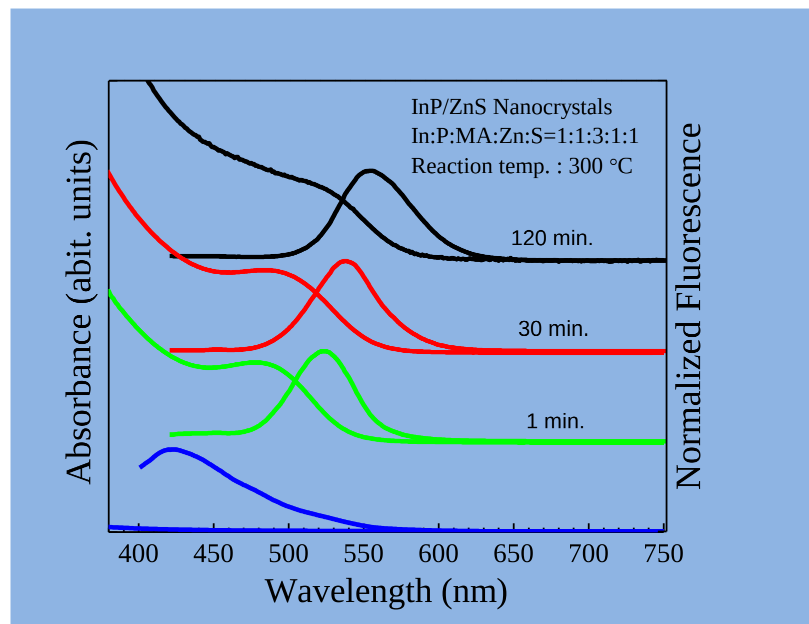
Growth of semiconductor Nanocrystals and metallic nanoparticles

Growth of InP/ZnS Nanocrystals



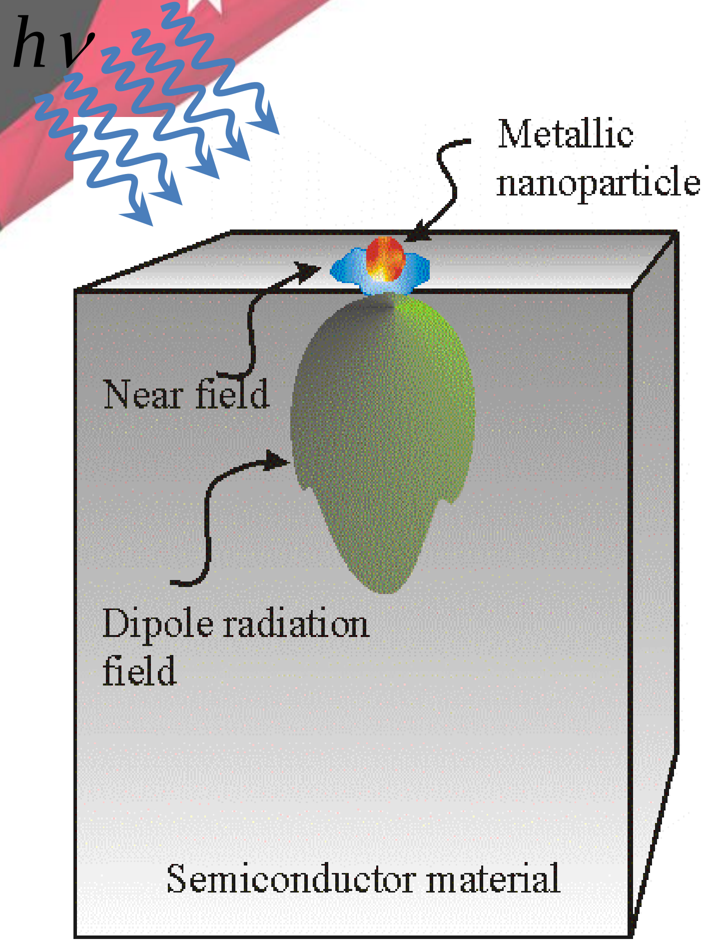


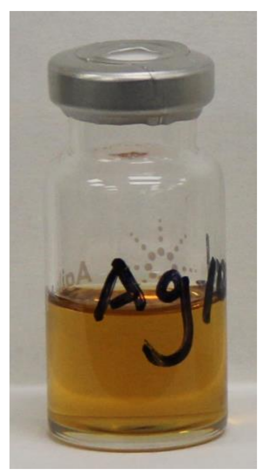
UV light off UV light on

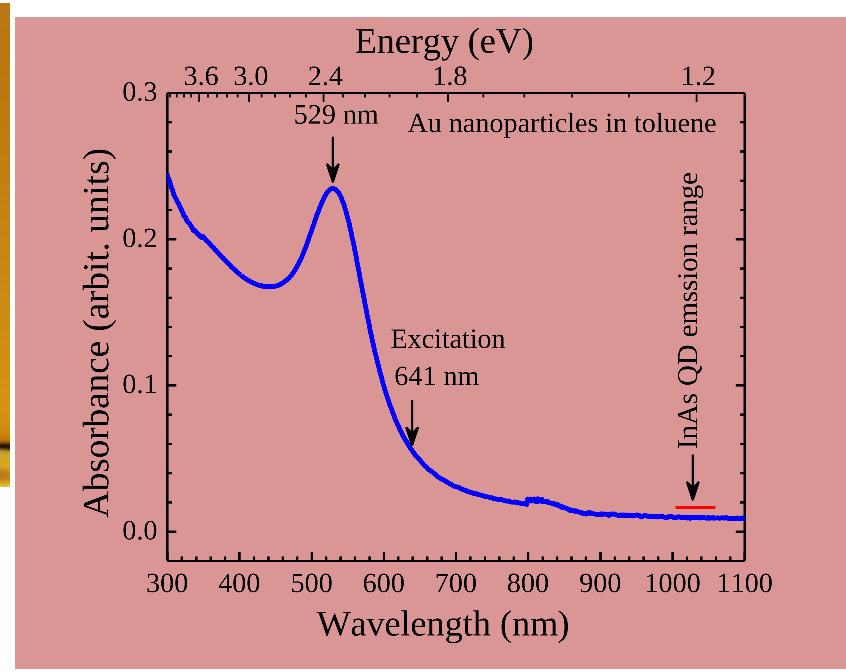


UV light off UV light on

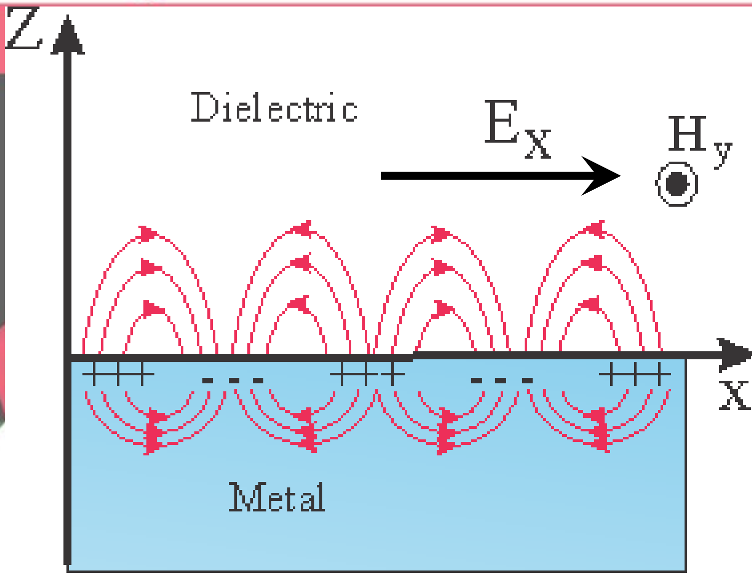
Plasmonic effect

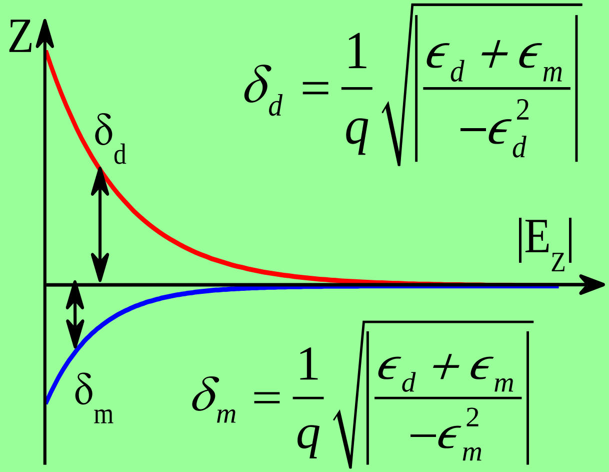






Plasmon dispersion



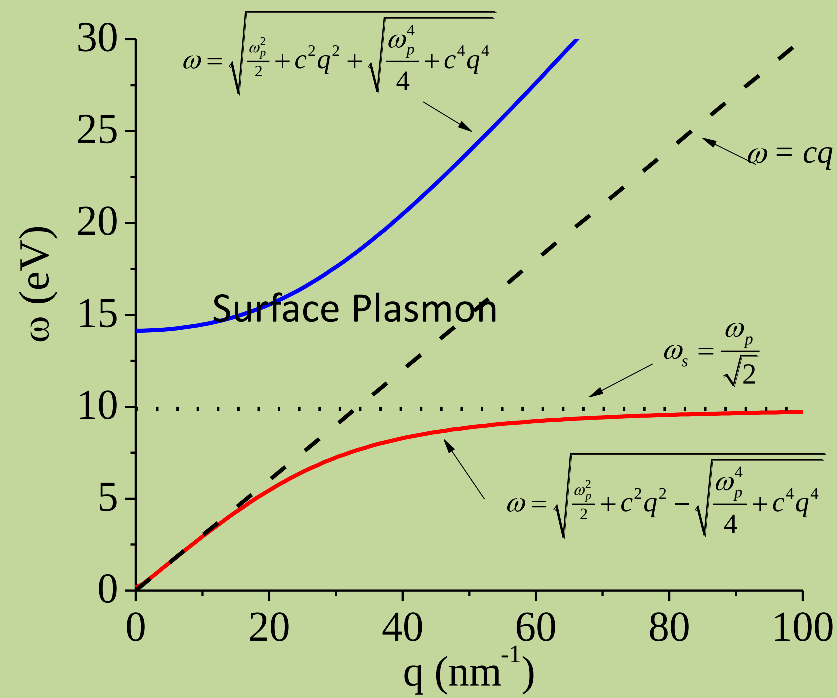


$$\delta_d = \frac{1}{q}\sqrt{\left|\frac{\epsilon_d + \epsilon_m}{-\epsilon_d^2}\right|}$$

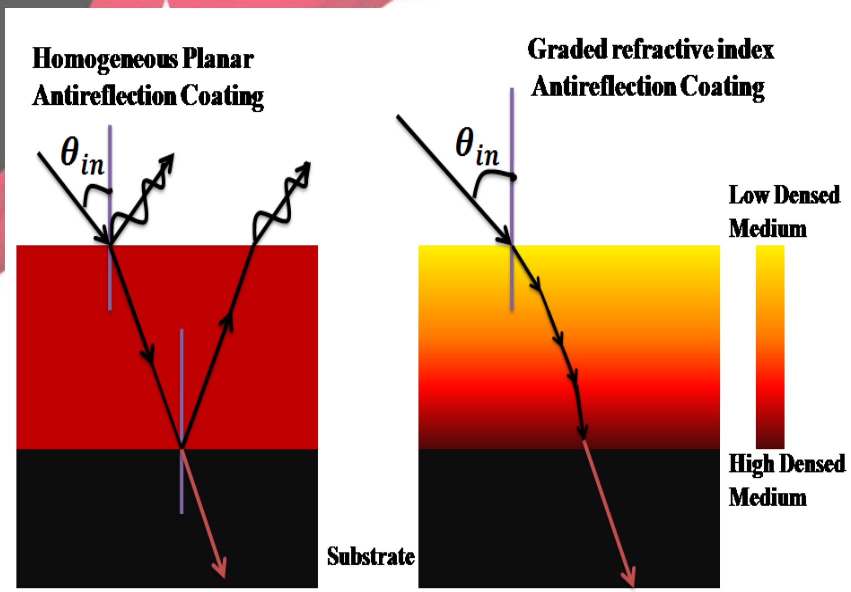
$$\delta_m = \frac{1}{q}\sqrt{\left|\frac{\epsilon_d + \epsilon_m}{-\epsilon_m^2}\right|}$$

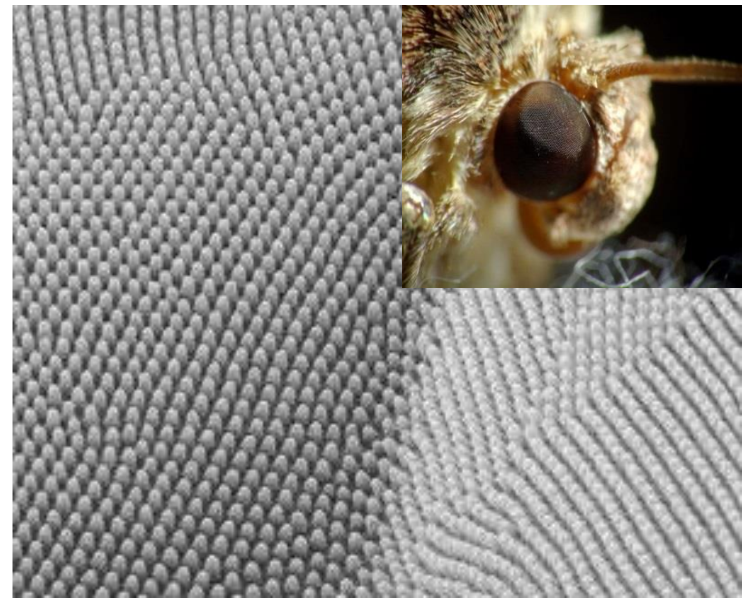
$q = \dfrac{\omega}{c}$ propgation in free space

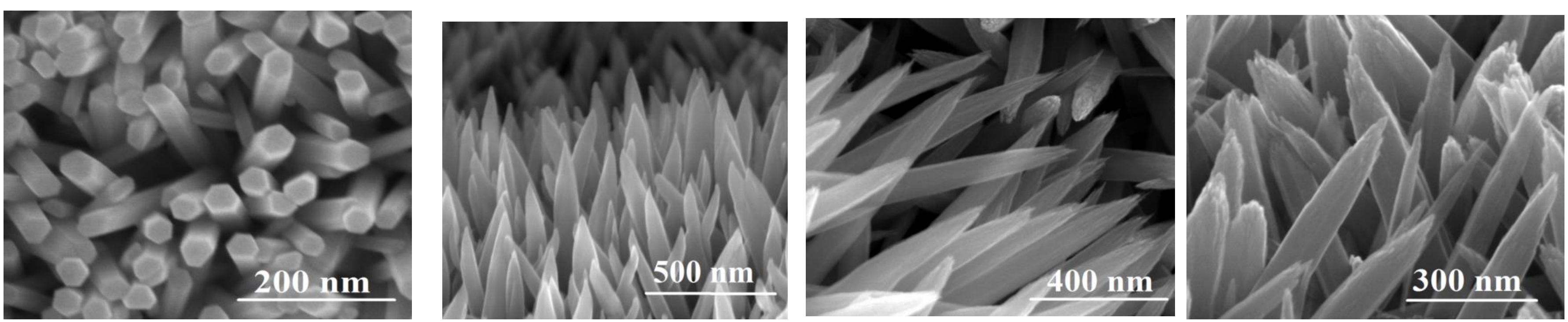
Bulk Plasmon



Anti-reflection Coating of Solar Cells







ZnO nanorods

- Sol-gel technique is employed to synthesize metal oxide antireflection coating.
- Hydrolysis of metal precursors is carried out to form the sol gel.

Titanium Dioxide sol-gel

Titanium tetra isopropoxide (TTIP)

2-propanol

0.5M TTIP solution

Hydrolysis with H_2O

pH control with HCl

Titanium Dioxide sol-gel

Zinc Oxide sol-gel

Zinc acetate dihydate (ZnAc)

2-propanol

0.5M ZnAc solution

Hydrolysis with ethanolamine

Zinc oxide sol-gel

Tantalum pentoxide sol-gel

Tantalum ethoxide (TaEt)

2Methoxy ethanol

0.02M TaEt solution

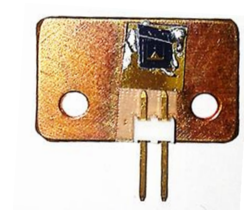
Hydrolysis with H_2O

pH control with Diethanolamine

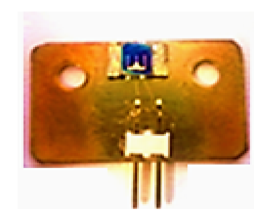
Tantalum pentoxide sol-gel

Transparent sol-gel synthesized by hydrolysis.

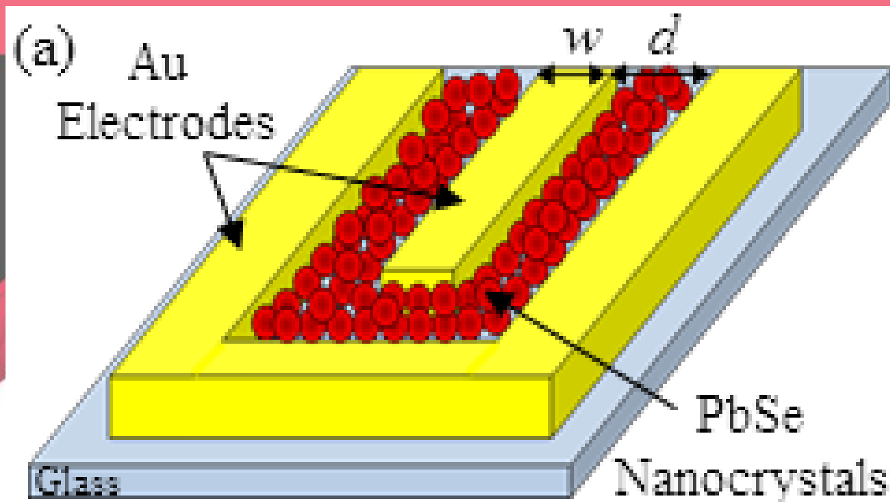
Spin coated sol-gel films with increasing coating speed on GaAs. Samples from the left, pristine, 4000,6000, 8000, 10000 and 12000 rpm

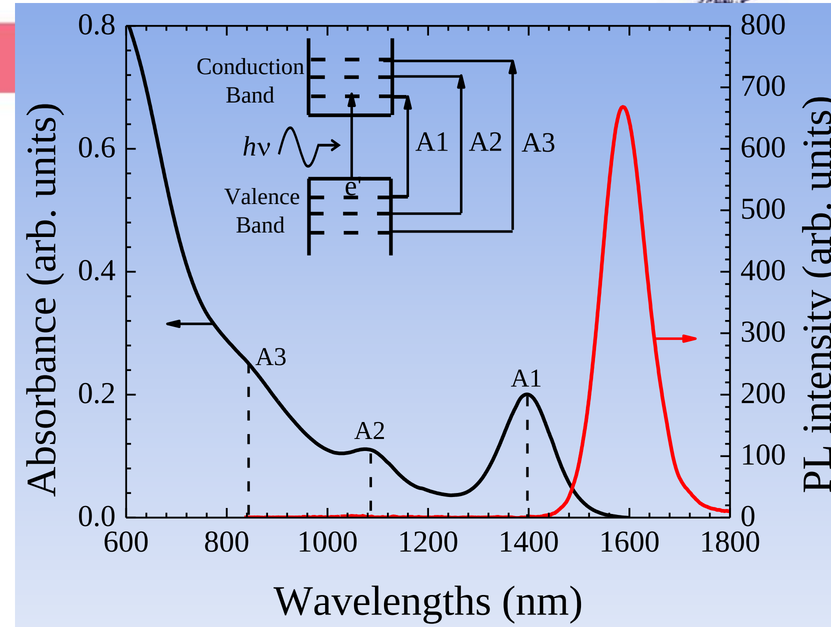


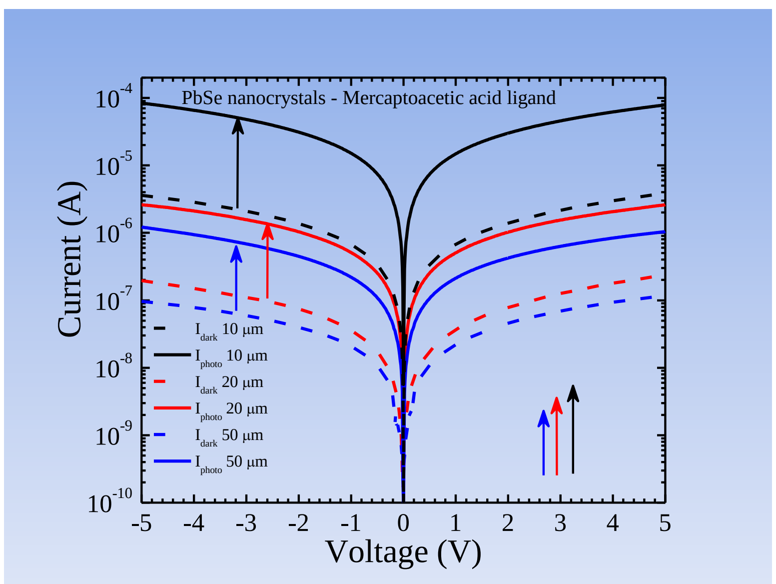
Pristine solar cell

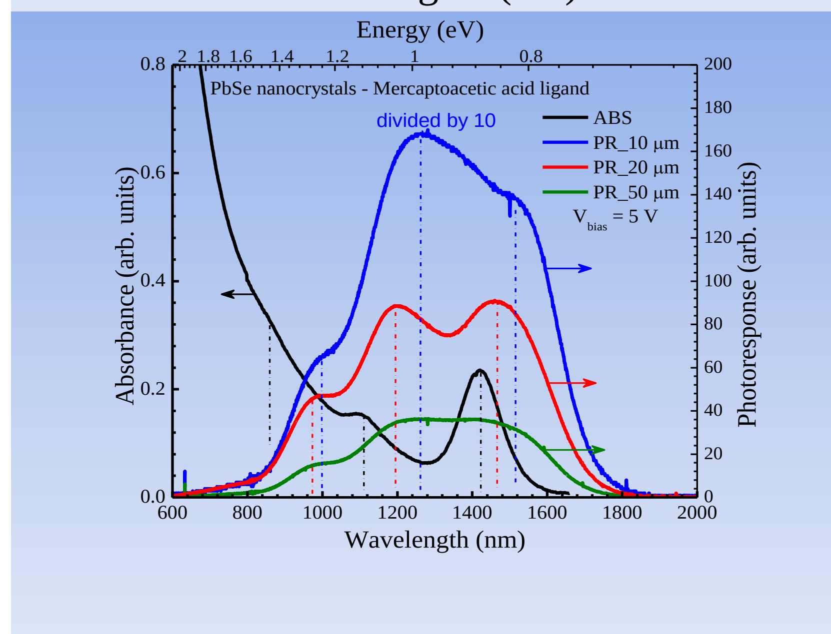


Solar cell with coating

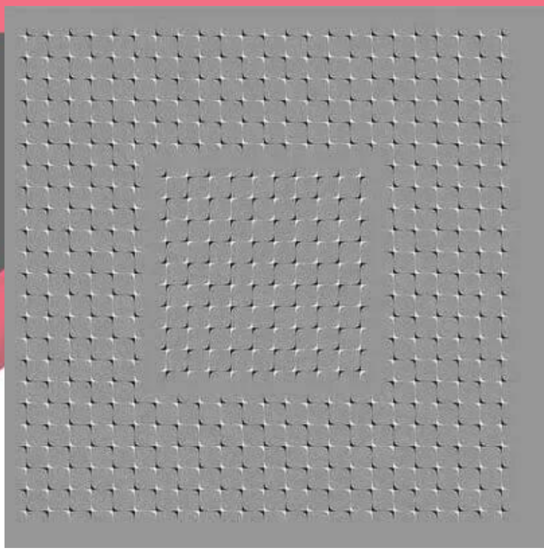

(a)
Au
Electrodes
w
d
PbSe
Nanocrystals
Glass

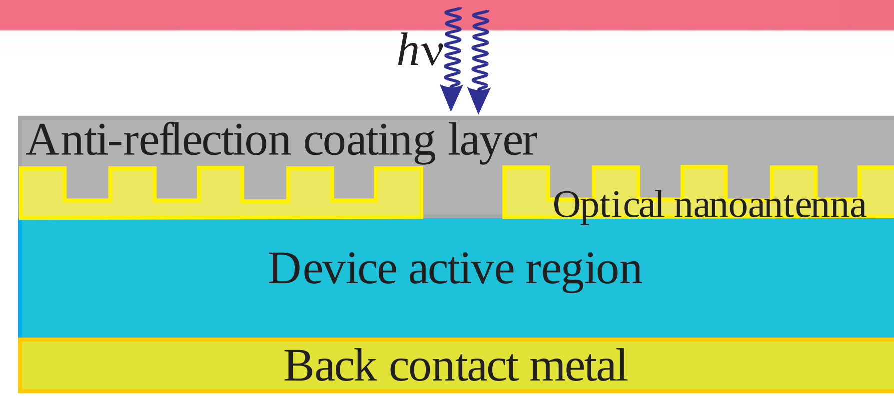

Conduction
Band
Valence
Band
hν
e
A1
A2
A3
Absorbance (arb. units)
PL intensity (arb. units)
Wavelengths (nm)
0.0
0.2
0.4
0.6
0.8
0
100
200
300
400
500
600
700
800
600
800
1000
1200
1400
1600
1800

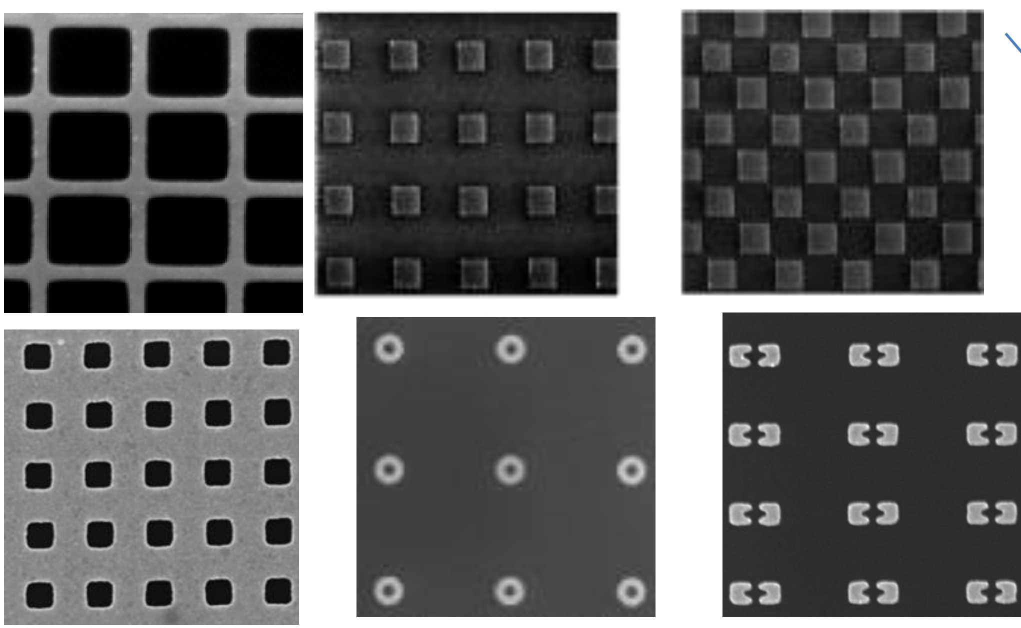

PbSe nanocrystals - Mercaptoacetic acid ligand
Current (A)
Voltage (V)
I_{dark} 10 µm
I_{photo} 10 µm
I_{dark} 20 µm
I_{photo} 20 µm
I_{dark} 50 µm
I_{photo} 50 µm
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
-5
-4
-3
-2
-1
0
1
2
3
4
5

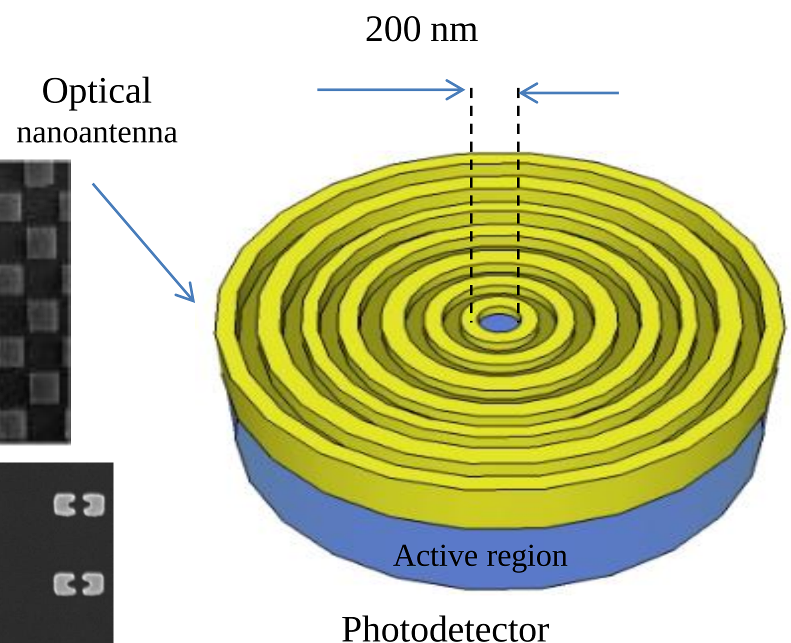

Energy (eV)
2
1.8
1.6
1.4
1.2
1
0.8
PbSe nanocrystals - Mercaptoacetic acid ligand
divided by 10
ABS
PR_10 µm
PR_20 µm
PR_50 µm
V_{bias} = 5 V
Absorbance (arb. units)
Photoresponse (arb. units)
Wavelength (nm)
0.0
0.2
0.4
0.6
0.8
0
20
40
60
80
100
120
140
160
180
200
600
800
1000
1200
1400
1600
1800
2000

Metasurfaces and nanoantennas coupled photodetectors

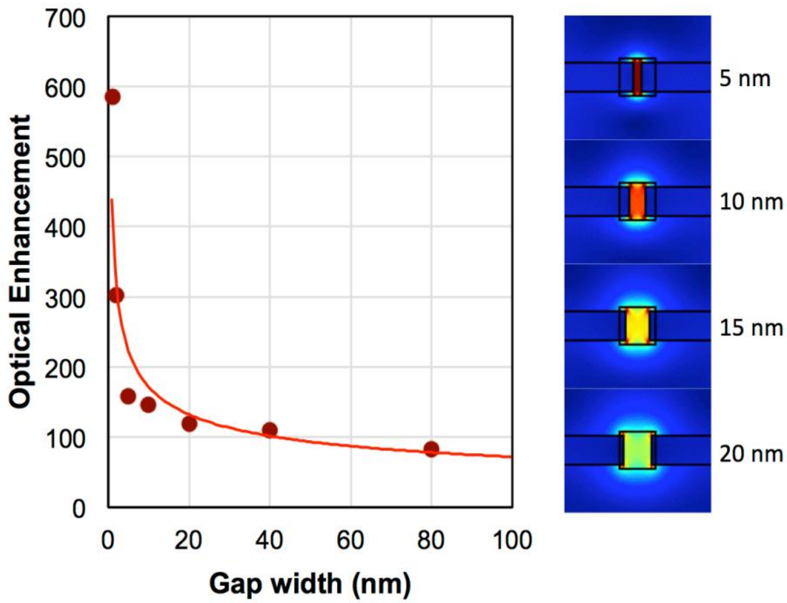


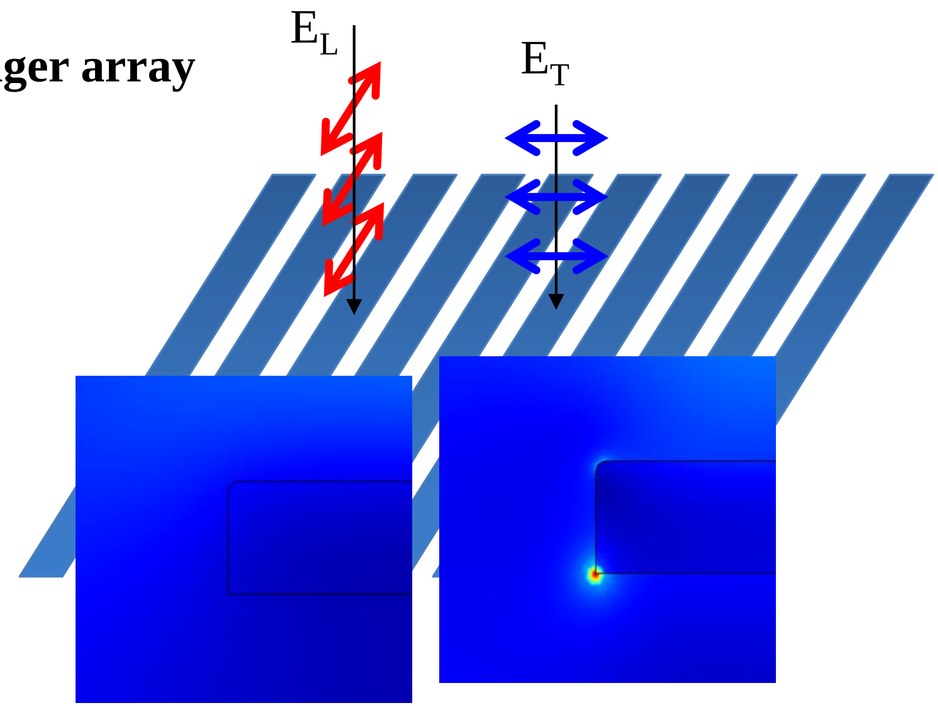






COMSOL FEM Model of Au interdigital finger array



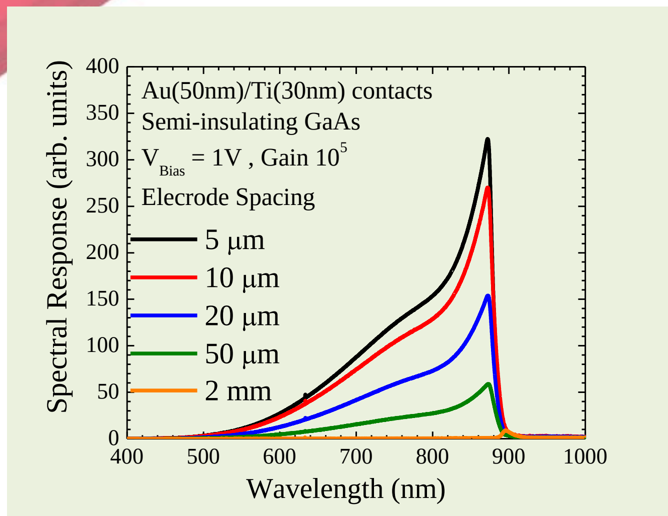


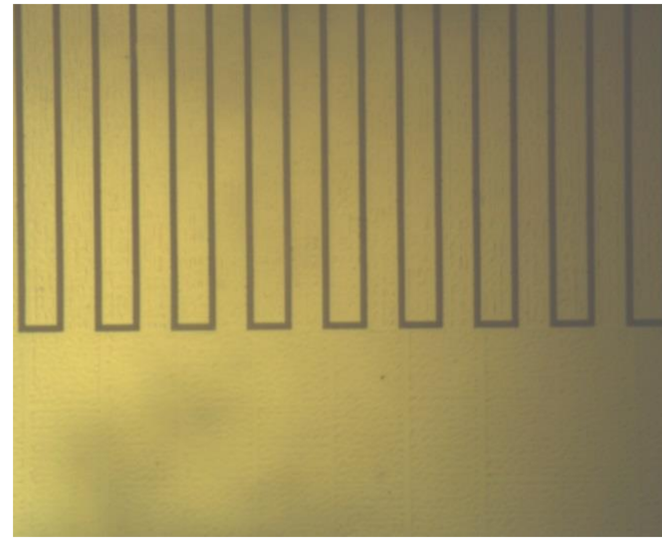
Longitudinal Polarization **Transverse Polarization**

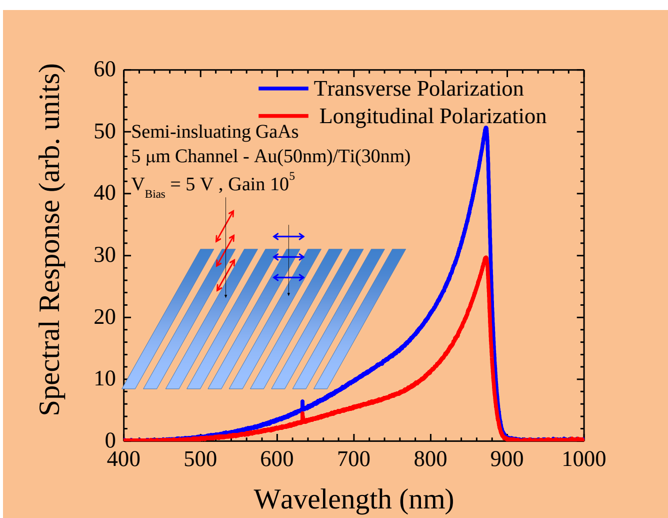
max = 1.6 max = 7.49

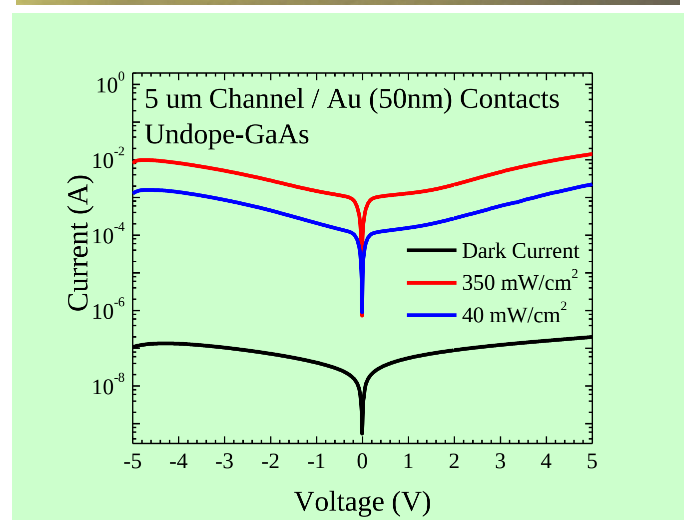
Wavelength = 550 nm

Optical enhancement = E_{loc}/E_0

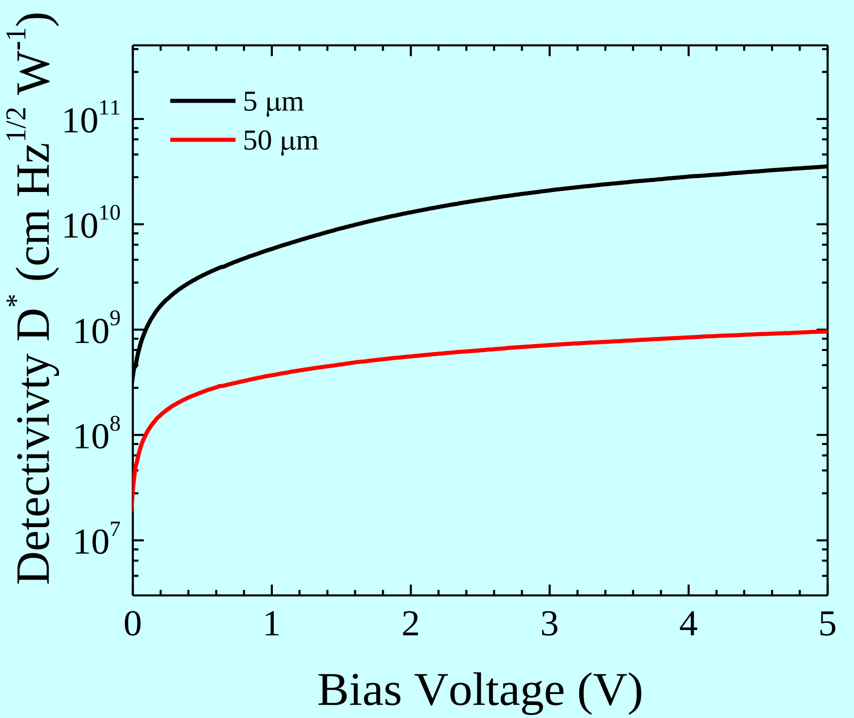

Au(50nm)/Ti(30nm) contacts
Semi-insulating GaAs
V Bias = 1V , Gain 10^5
Elecrode Spacing
5 µm
10 µm
20 µm
50 µm
2 mm
Spectral Response (arb. units)
Wavelength (nm)
0
50
100
150
200
250
300
350
400
500
600
700
800
900
1000




Transverse Polarization
Longitudinal Polarization
Semi-insluating GaAs
5 µm Channel - Au(50nm)/Ti(30nm)
V Bias = 5 V , Gain 10^5
Spectral Response (arb. units)
Wavelength (nm)
0
10
20
30
40
50
60
400
500
600
700
800
900
1000


5 um Channel / Au (50nm) Contacts
Undope-GaAs
Dark Current
350 mW/cm^2
40 mW/cm^2
Current (A)
Voltage (V)
10^0
10^-2
10^-4
10^-6
10^-8
-5
-4
-3
-2
-1
0
1
2
3
4
5

Room Temperature Detectivity

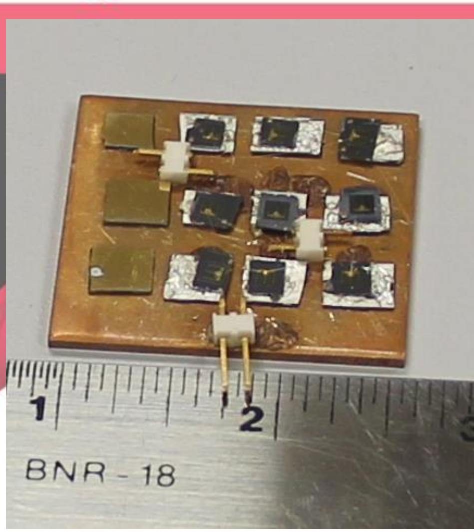


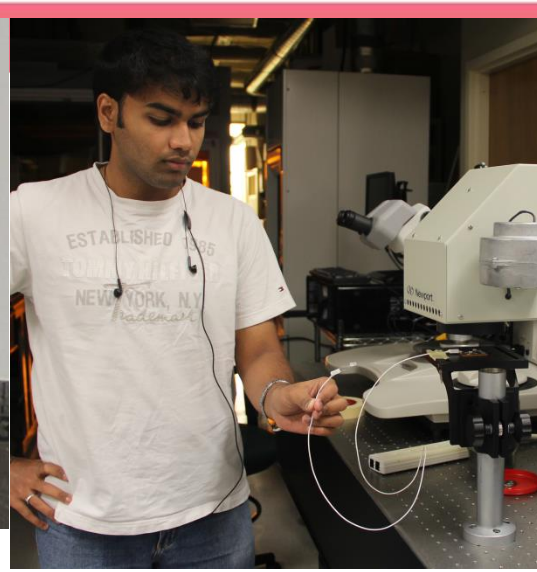
$$D^* = \frac{I_P \sqrt{A}}{P_{opt} \sqrt{2eI_D}}$$

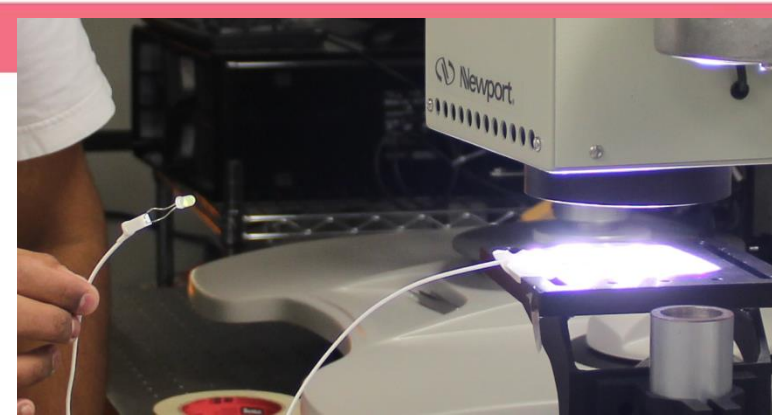
I_P = the photocurrent,
A = the device effective area,
$P_{opt.}$ = the incident optical power density, I_D = the dark current

Where do we go from here?

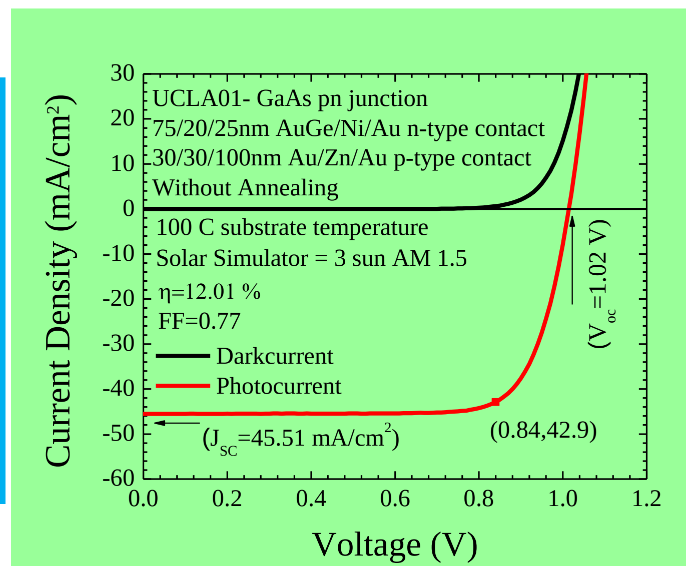
- Apply the plasmonic and anti-reflection approaches to solar cells to enhance their performance.
- Utilize the nanomaterials to fabricate sensors, such as electrochemical sensors and biosensors.
- Utilize the nanomaterials to fabricate large area and high brightness LEDs for flat panel displays.

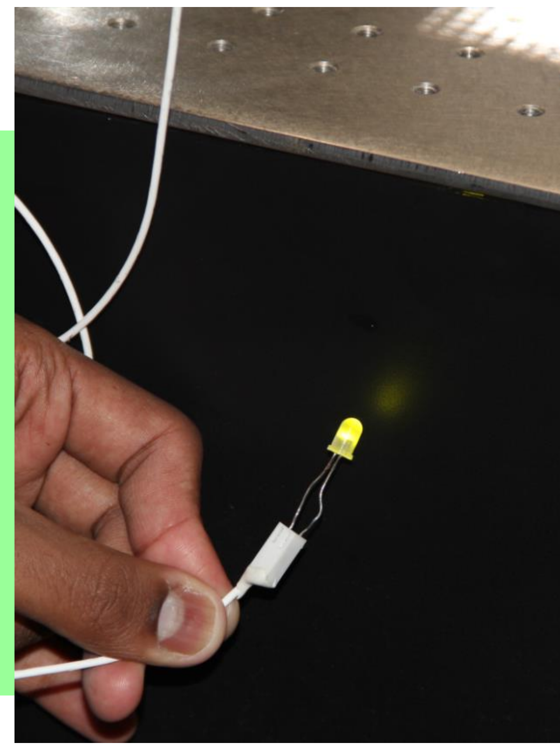


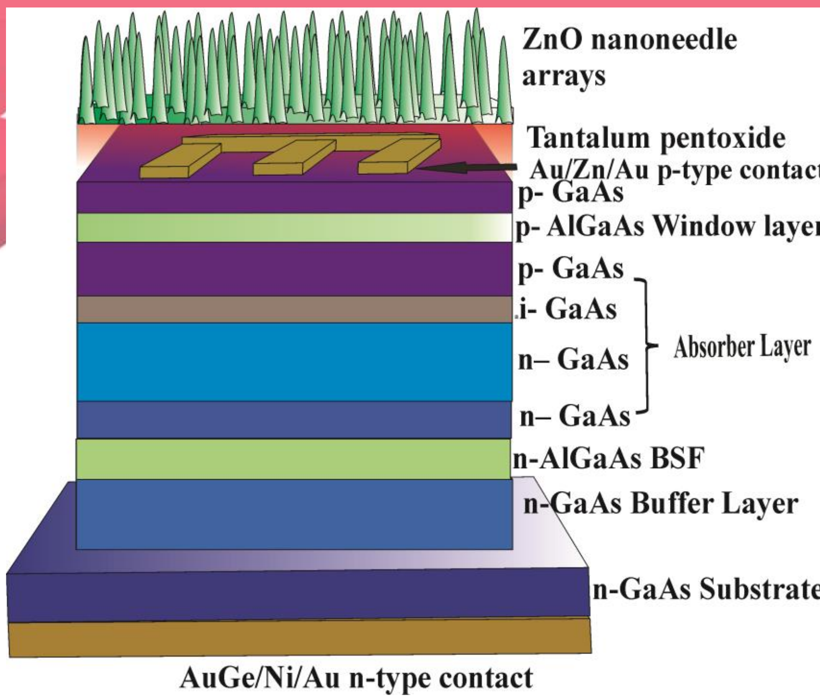


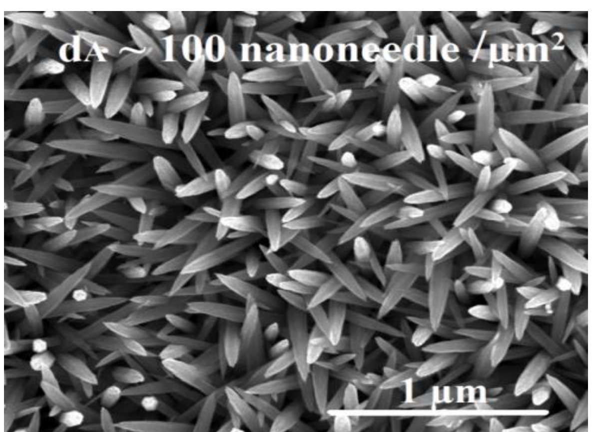


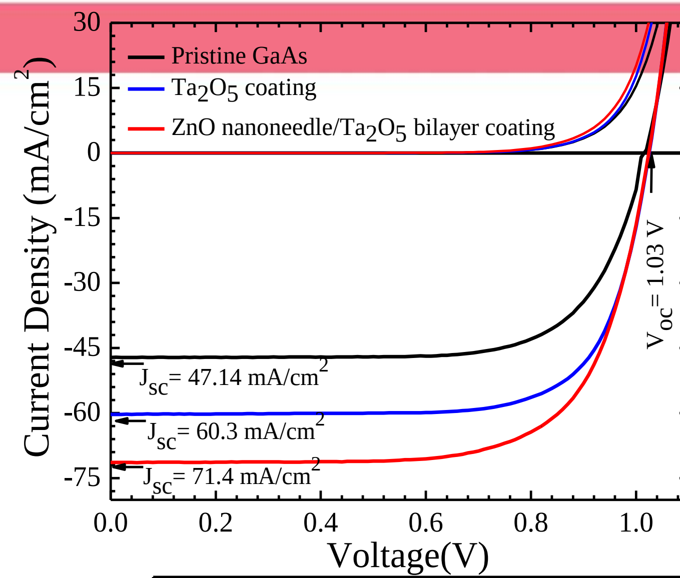
- Powering an LED Using GaAs pn junction solar cell.
- Total area of the nine devices is 0.81 cm^2.
- One sun AM1.5 solar simulator

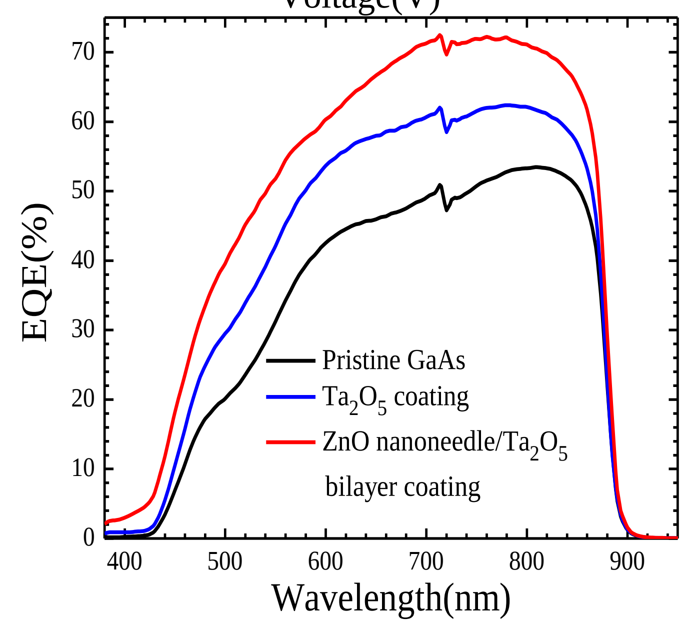




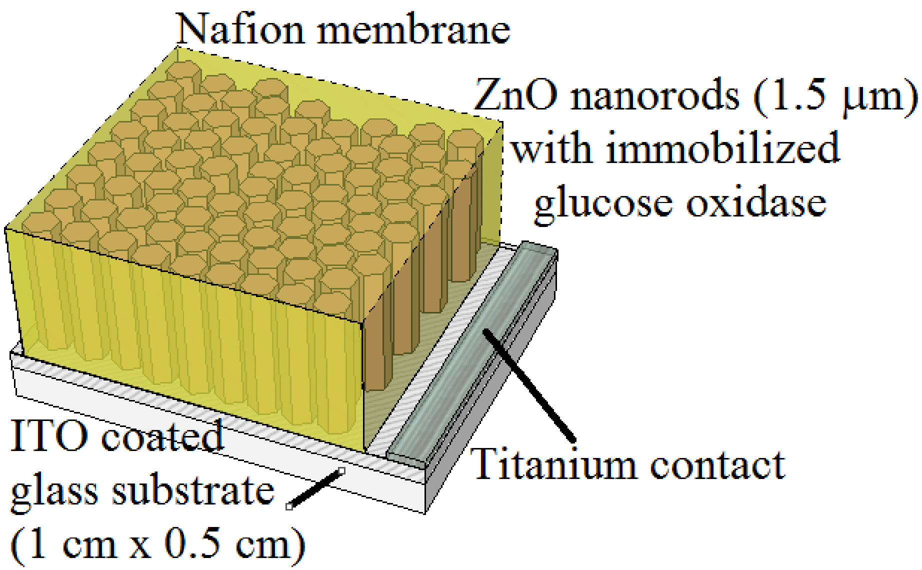

ZnO nanoneedle arrays
Tantalum pentoxide
Au/Zn/Au p-type contact
p- GaAs
p- AlGaAs Window layer
p- GaAs
i- GaAs
n– GaAs
n– GaAs
Absorber Layer
n-AlGaAs BSF
n-GaAs Buffer Layer
n-GaAs Substrate
AuGe/Ni/Au n-type contact

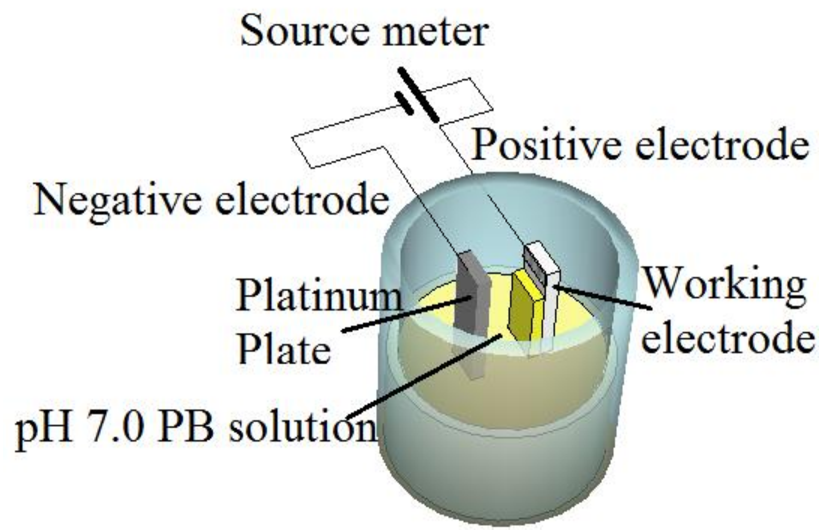

dA ~ 100 nanoneedle /µm²
1 µm

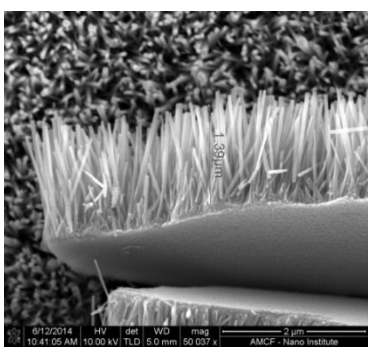

Pristine GaAs
Ta_2O_5 coating
ZnO nanoneedle/Ta_2O_5 bilayer coating
Current Density (mA/cm^2)
Voltage(V)
J_{sc}= 47.14 mA/cm^2
J_{sc}= 60.3 mA/cm^2
J_{sc}= 71.4 mA/cm^2
V_{oc}= 1.03 V
30
15
0
-15
-30
-45
-60
-75
0.0
0.2
0.4
0.6
0.8
1.0

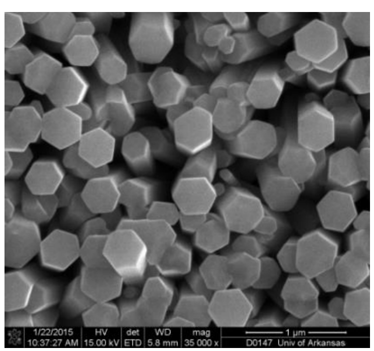

EQE(%)
Wavelength(nm)
Pristine GaAs
Ta_2O_5 coating
ZnO nanoneedle/Ta_2O_5
bilayer coating
0
10
20
30
40
50
60
70
400
500
600
700
800
900

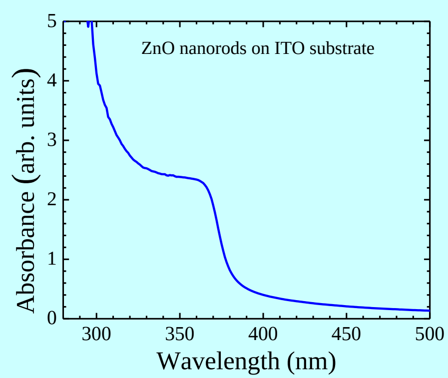
Biosensors: Glucose sensor based on ZnO Nanorods

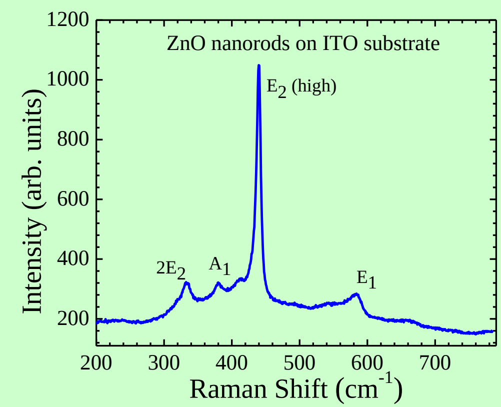




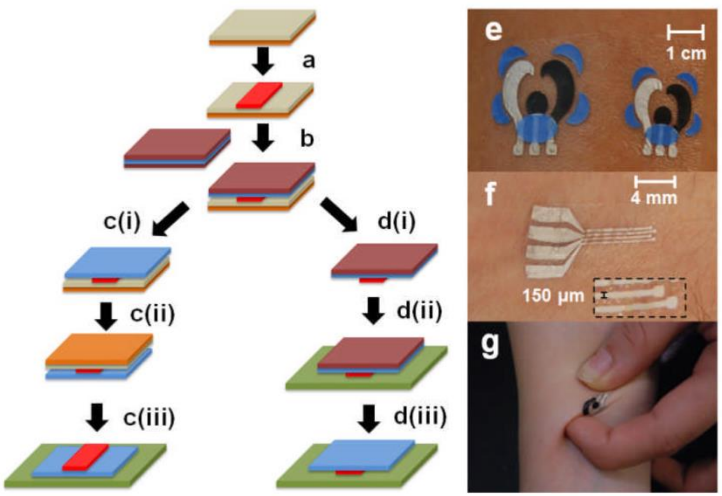


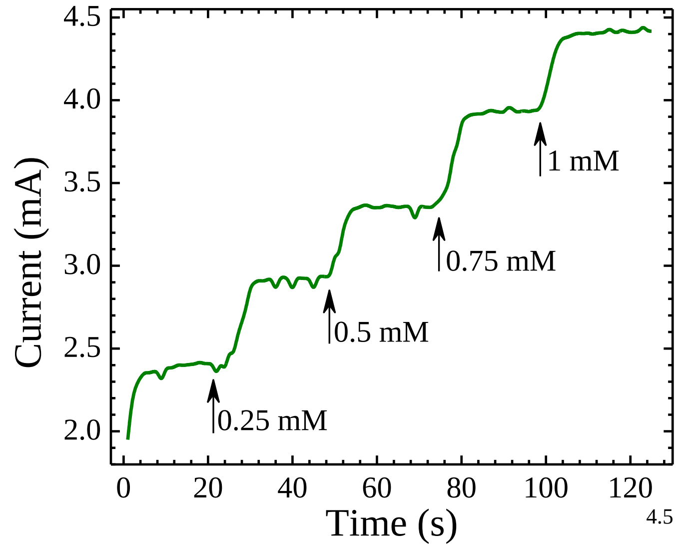


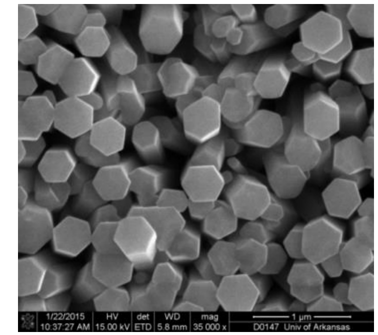




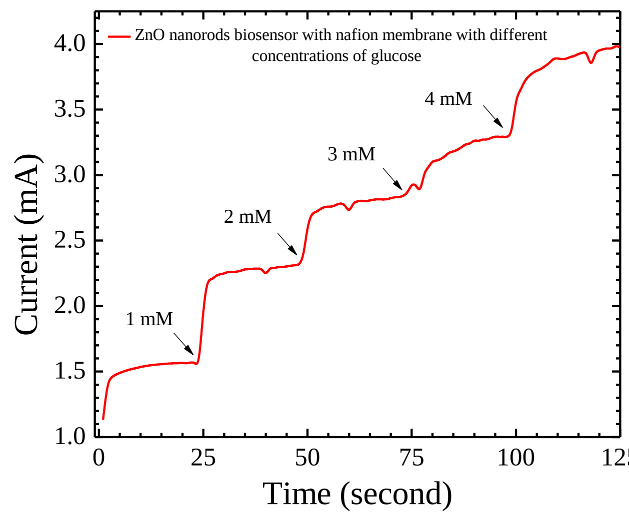
Electrochemical sensors: Glucose sensor based on ZnO Nanorods

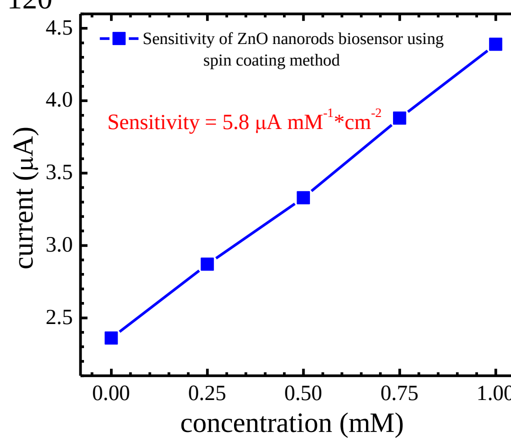






ZnO/ITO/Glass





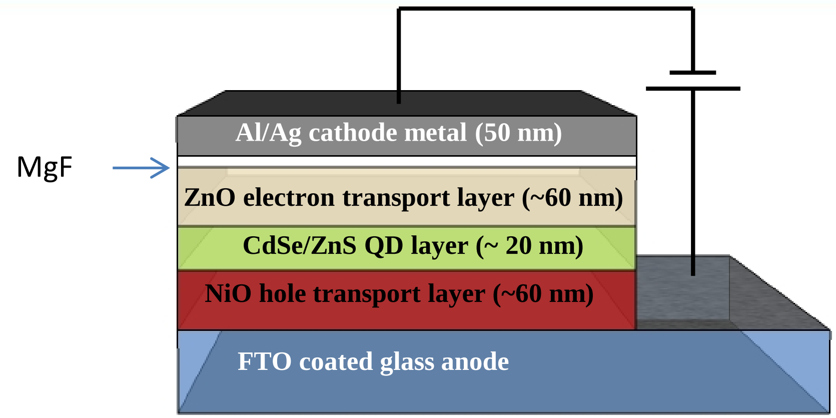
Chem Commun (Camb). Author manuscript; available in PMC 2013 July 11. Joseph Wang: josephwang@ucsd.edu

QDLED

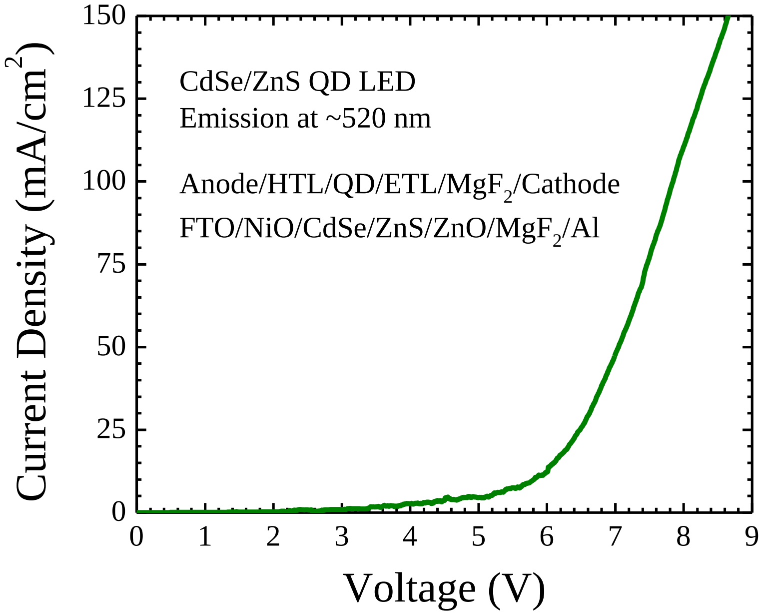
Light off **light on**
CdSe/ZnS core/Shell nanocrystals

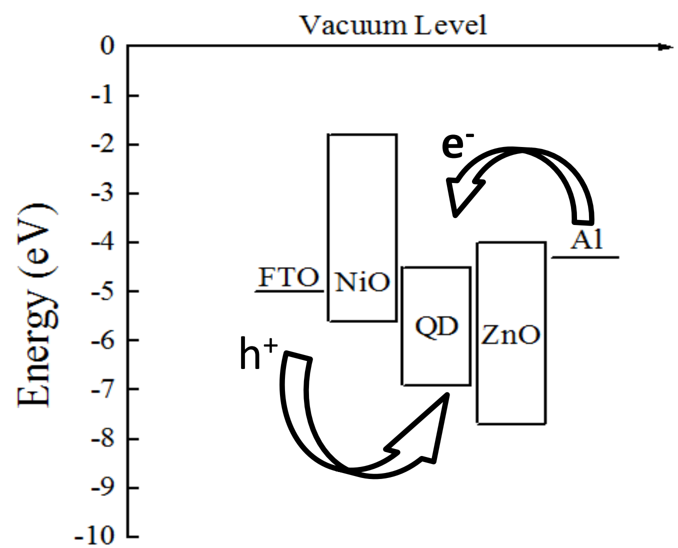
Zero bias voltage

QDLED biased with 10 V



Schematic of a colloidal Quantum dot LED (QDLED) device structure with charge transport layers.





Questions