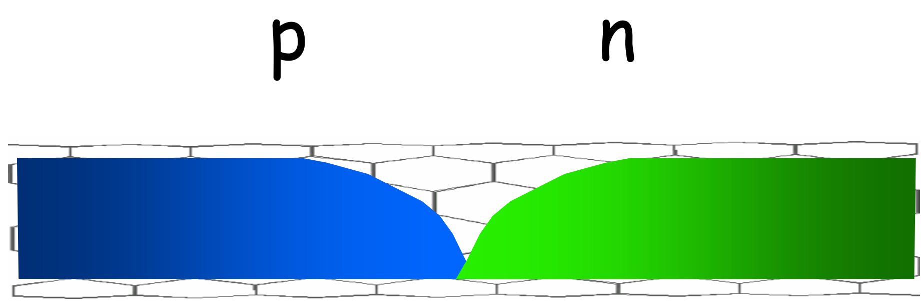
Optical Spectroscopy of Carbon Nanotube *p-n* Junction Diodes

Ji Ung Lee

College of Nanoscale Science and Engineering
University at Albany-SUNY



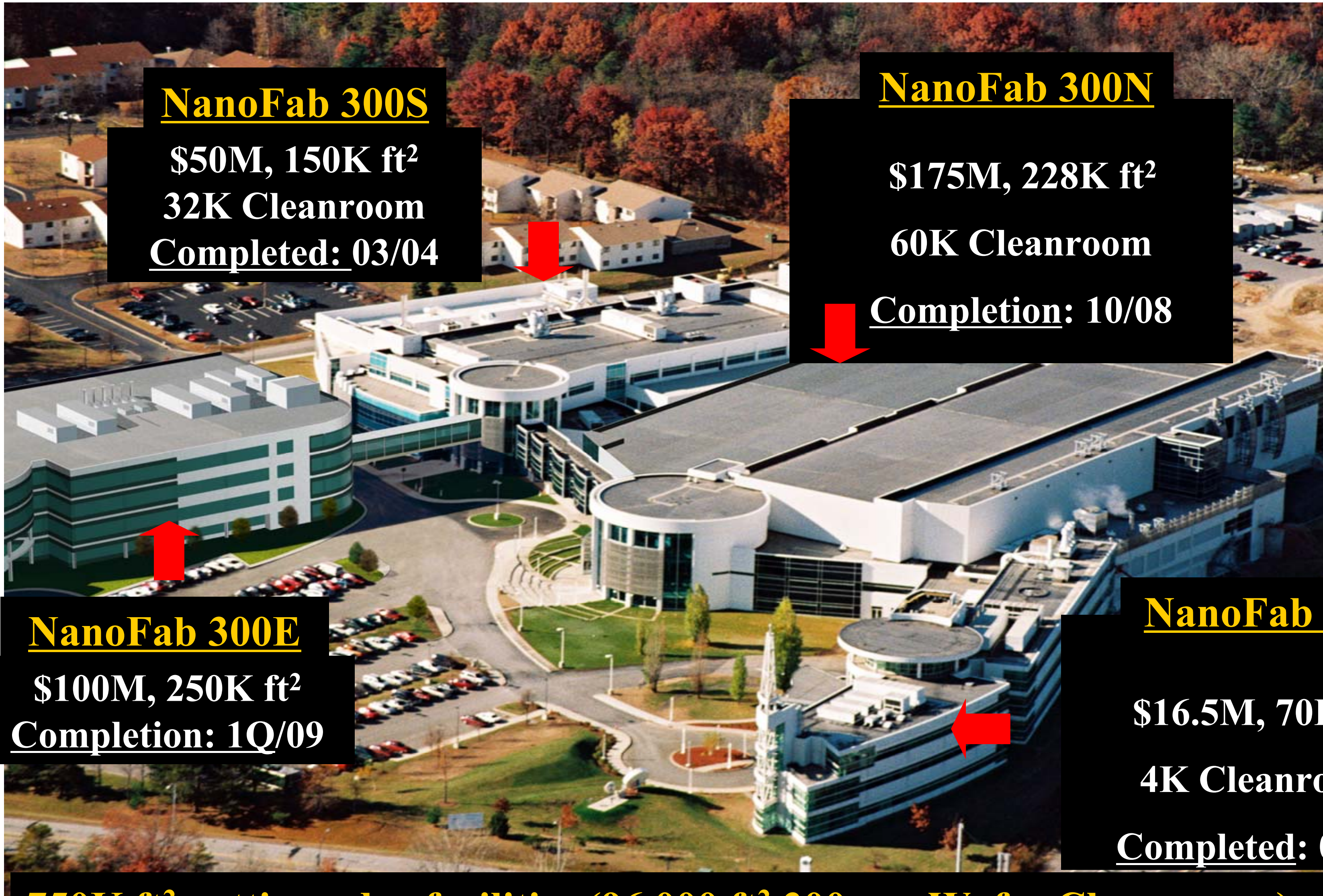
6th US-Korea Forum on Nanotechnology

April 28-29, 2009

The College of Nanoscale Science & Engineering and Albany NanoTech Complex at the University at Albany

jlee1@uamail.albany.edu

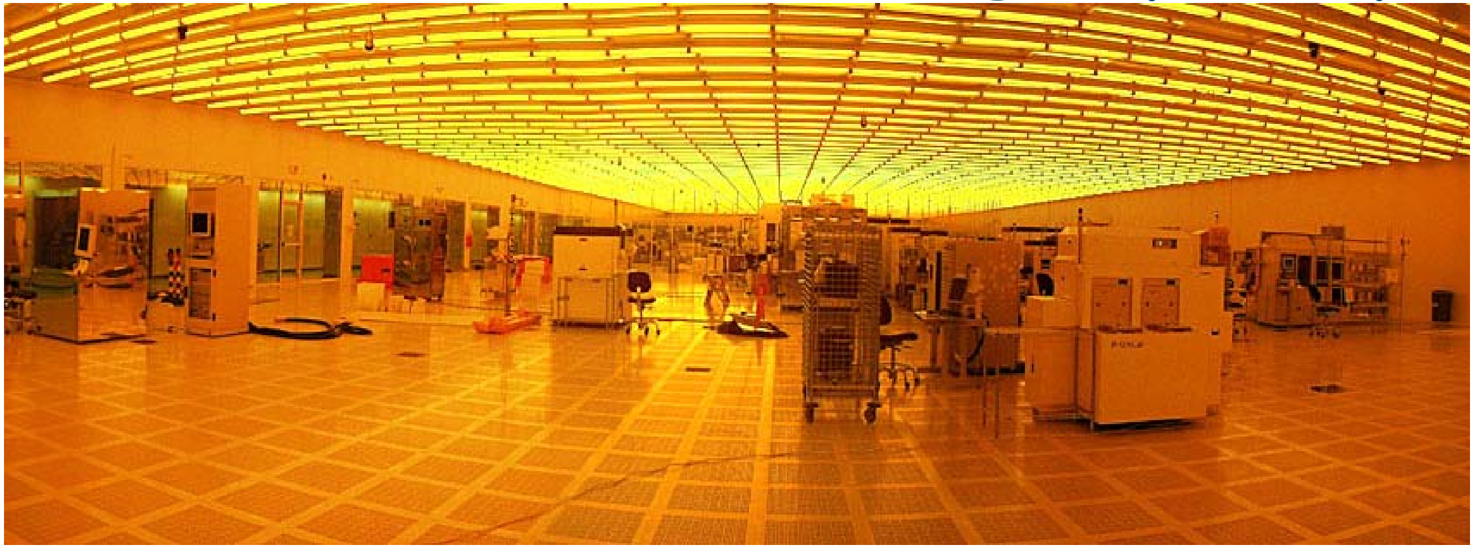
State-of-the-Art Infrastructure



750K ft² cutting-edge facilities (96,000 ft² 300mm Wafer Cleanrooms).

$4.5B investments and 2500 R&D jobs on site.

300 mm Wafer Processing Capability



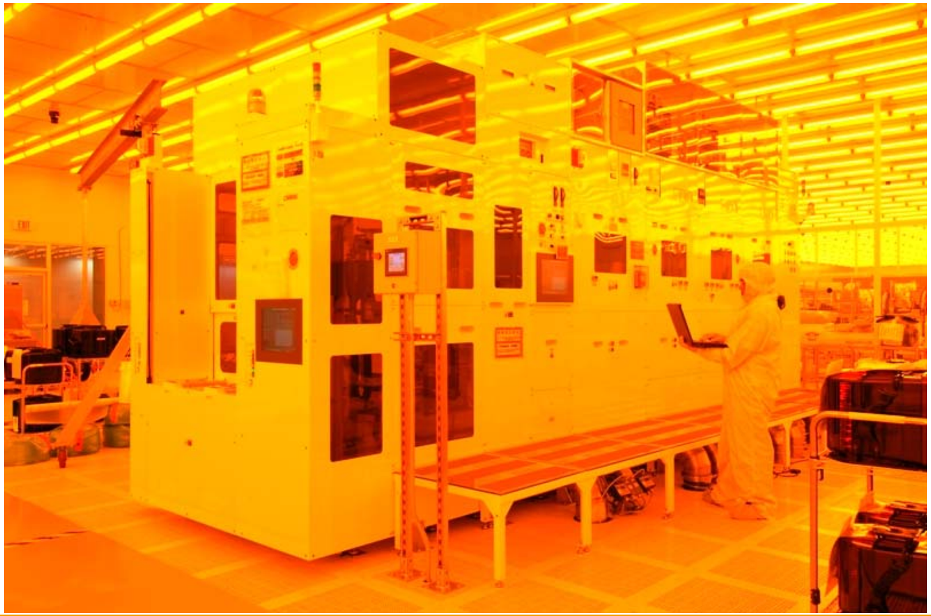
ANT/CNSE will house over 125 state-of-the-art 300mm wafer tools when build out is completed.

Designed for 32nm node & beyond but compatible with previous generations.

- Unit process, module integration, and full flow capability.
- Facility will have a 45nm baseline process for use by partners.

Facility capable of 25 integrated wafer starts (WSD) per day.

- 24/7 operation, wafer release 6 Days / Week



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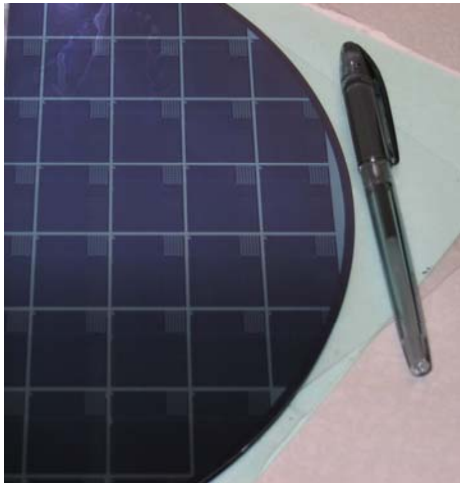
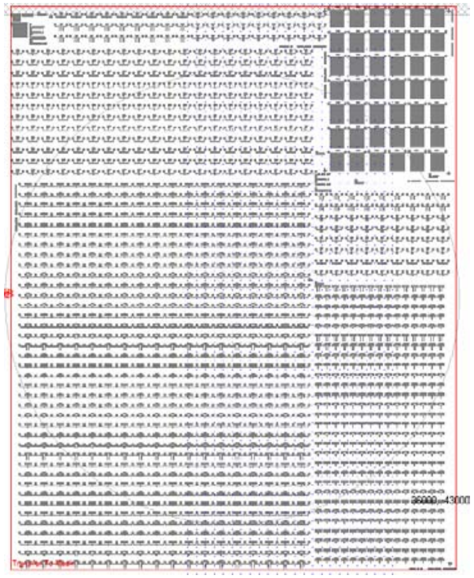
Device fabrication on 300mm wafers

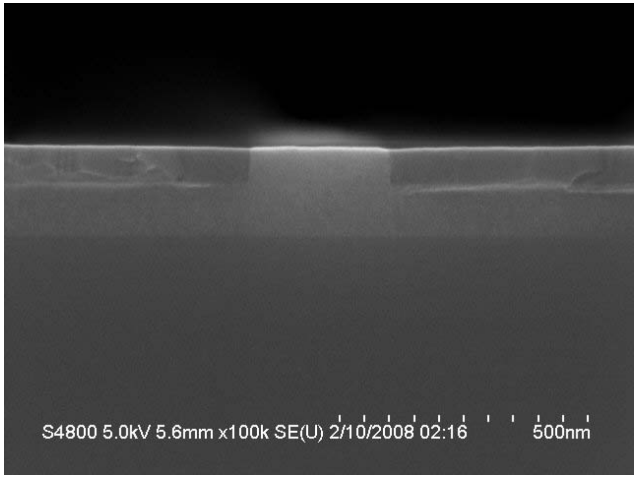


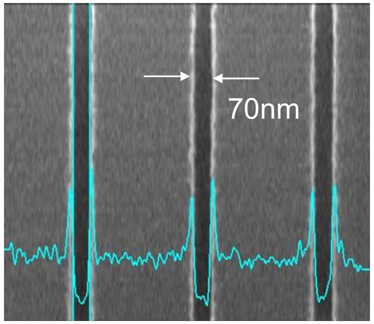
>1000 devices/die

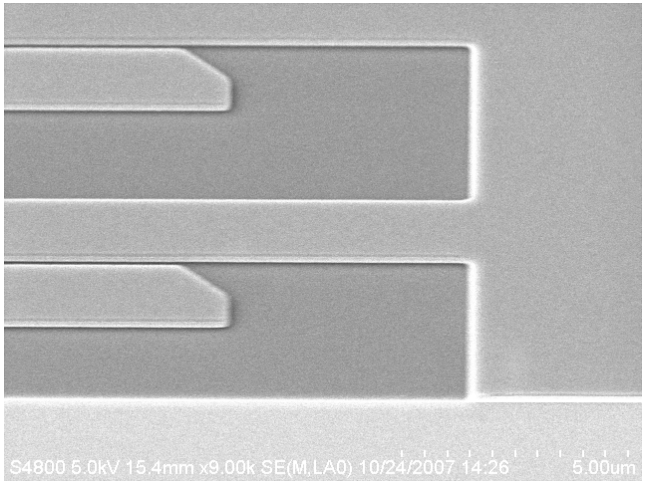
~100 nm features

Advanced processes









Why study the p-n diode:

- The p-n junction diode is the most fundamental of all the semiconductor devices – it is the basis for the majority of solid state devices.

- For fundamental understanding of semiconductors:
  Example: Hall-Shockley-Read Theory.

For any new semiconductor, a proper characterization of the p-n diode is important.

jlee1@uamail.albany.edu

Interplay between transport and optical properties:

- SWNT Diode Fabrication and DC Characteristics
- Optical Properties:
  - Photovoltaic Effect
  - Enhanced Optical Absorption - Excitons
- Origin of the Ideal Diode Behavior (BGR-Bandgap Shrinkage)

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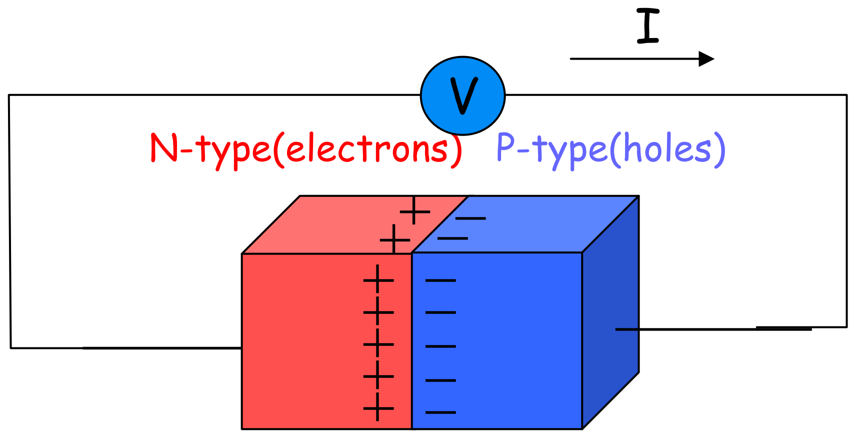
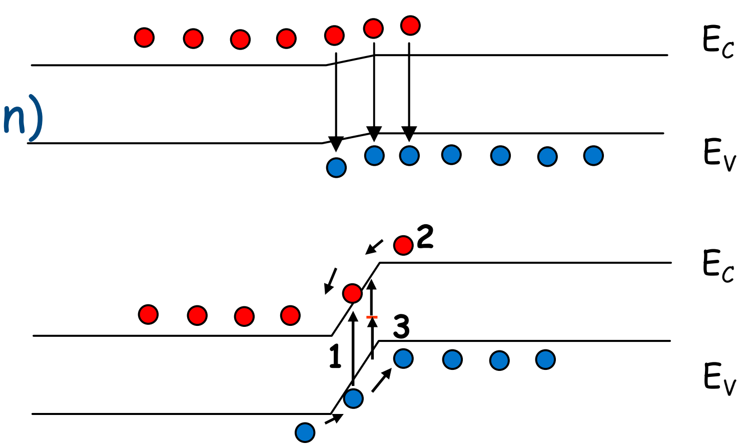
Bulk p-n junction diode basics:



Equilibrium

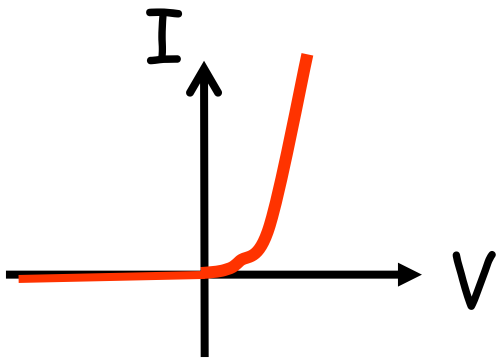
Forward Bias
(Recombination)

Reverse Bias
(Generation)



Diode Equation:
(ideal if n=1)

$$I = I_o\left(e^{qV/nKT} - 1\right)$$



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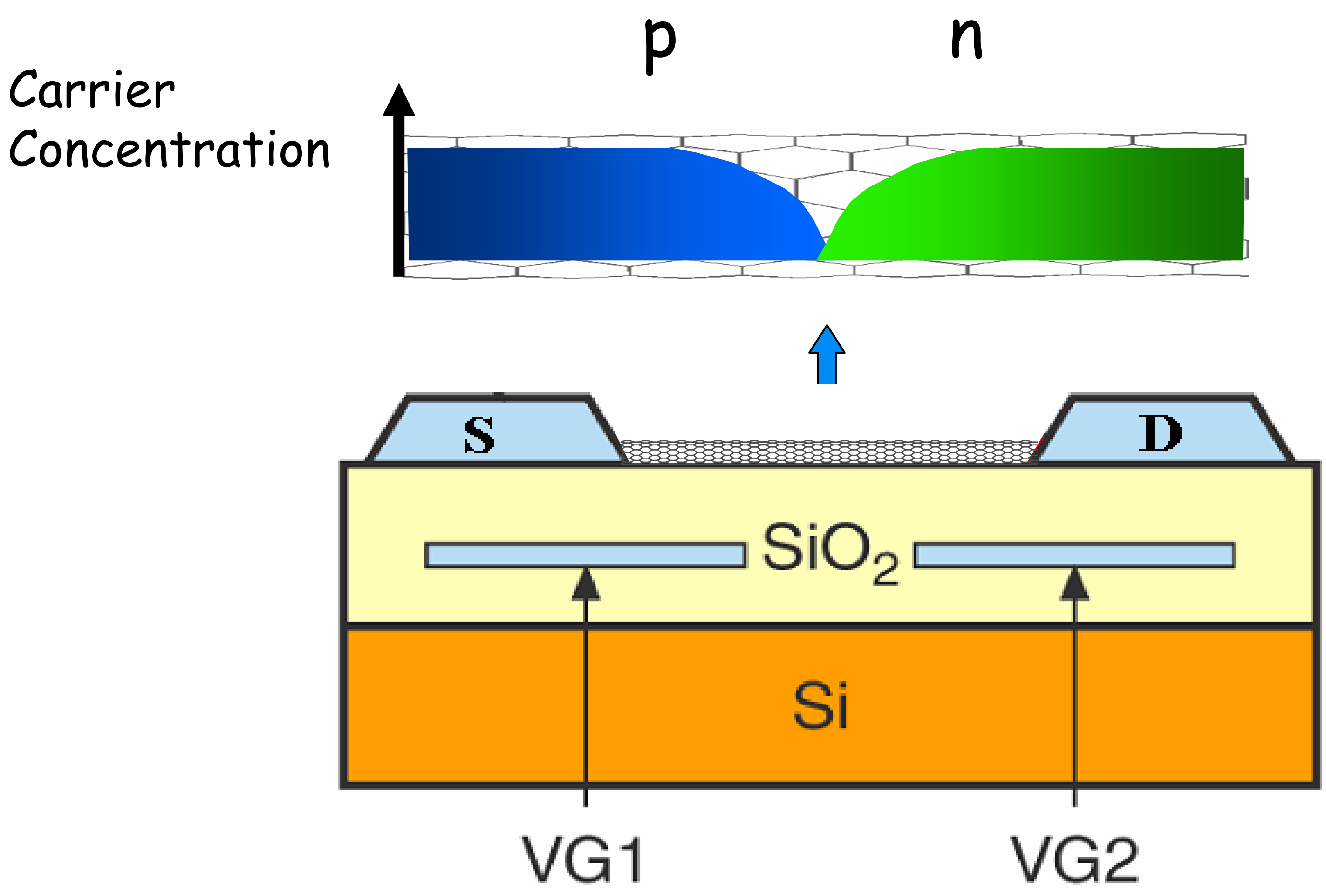
Electrostatic doping:



Split gates VG1,2

J.U. Lee et. al., APL: July 5, 2004

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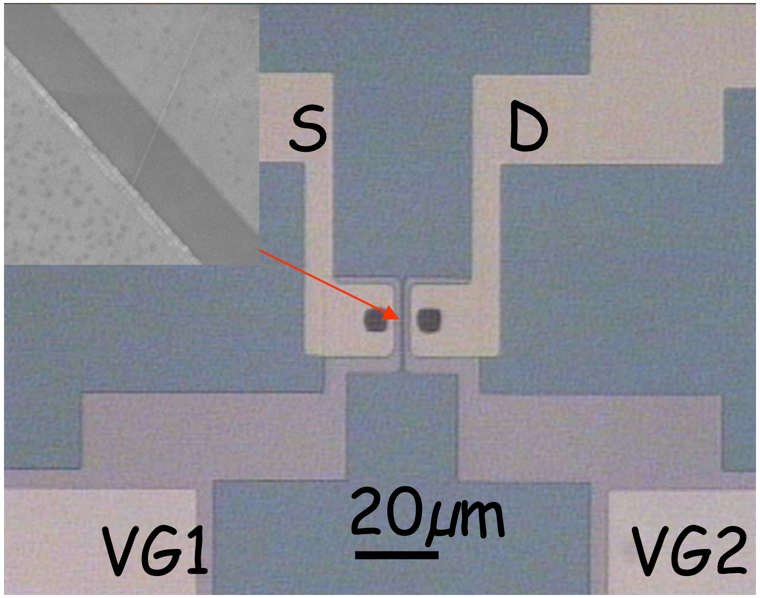
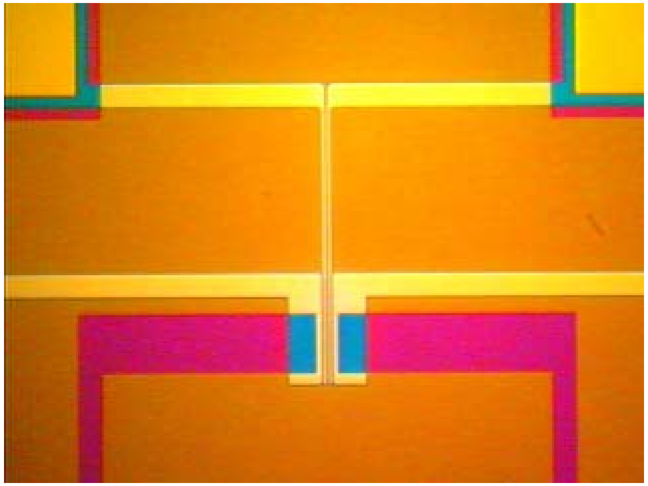
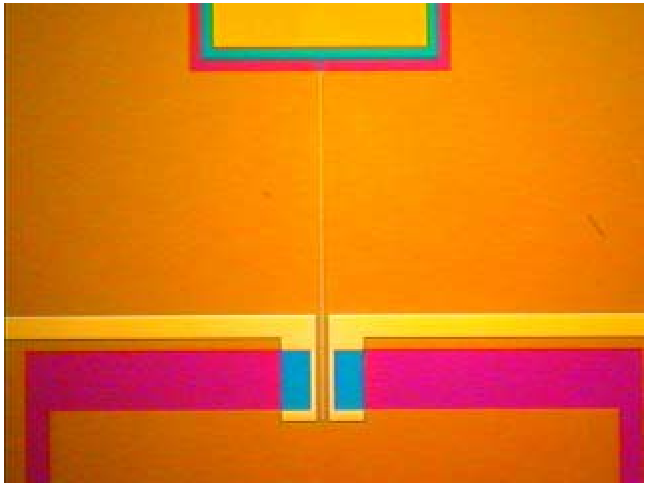
2 gate device





3 and 4
gate devices



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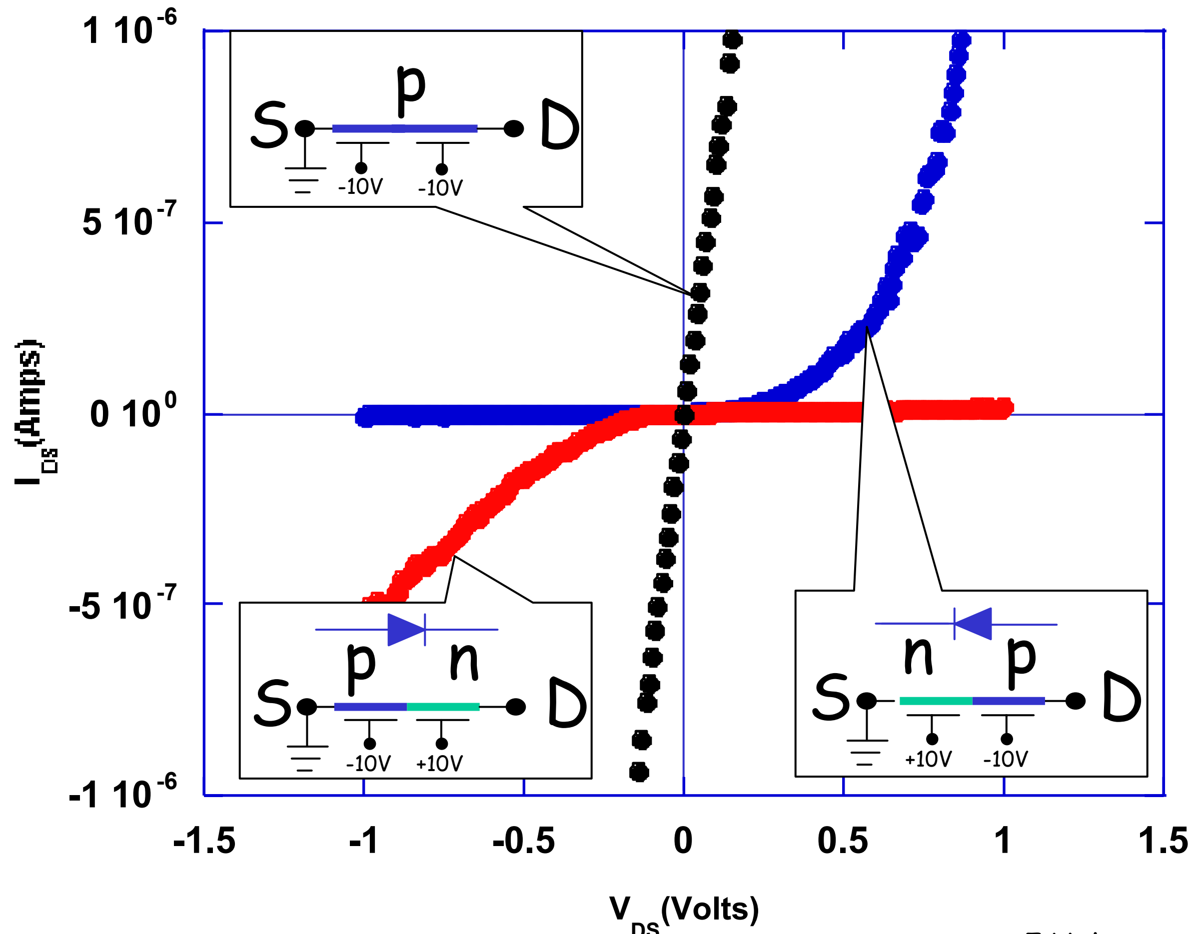
CNT diode/rectifier:
(p-n or n-p diode devices)



J.U. Lee et. al., APL: July 5, 2004

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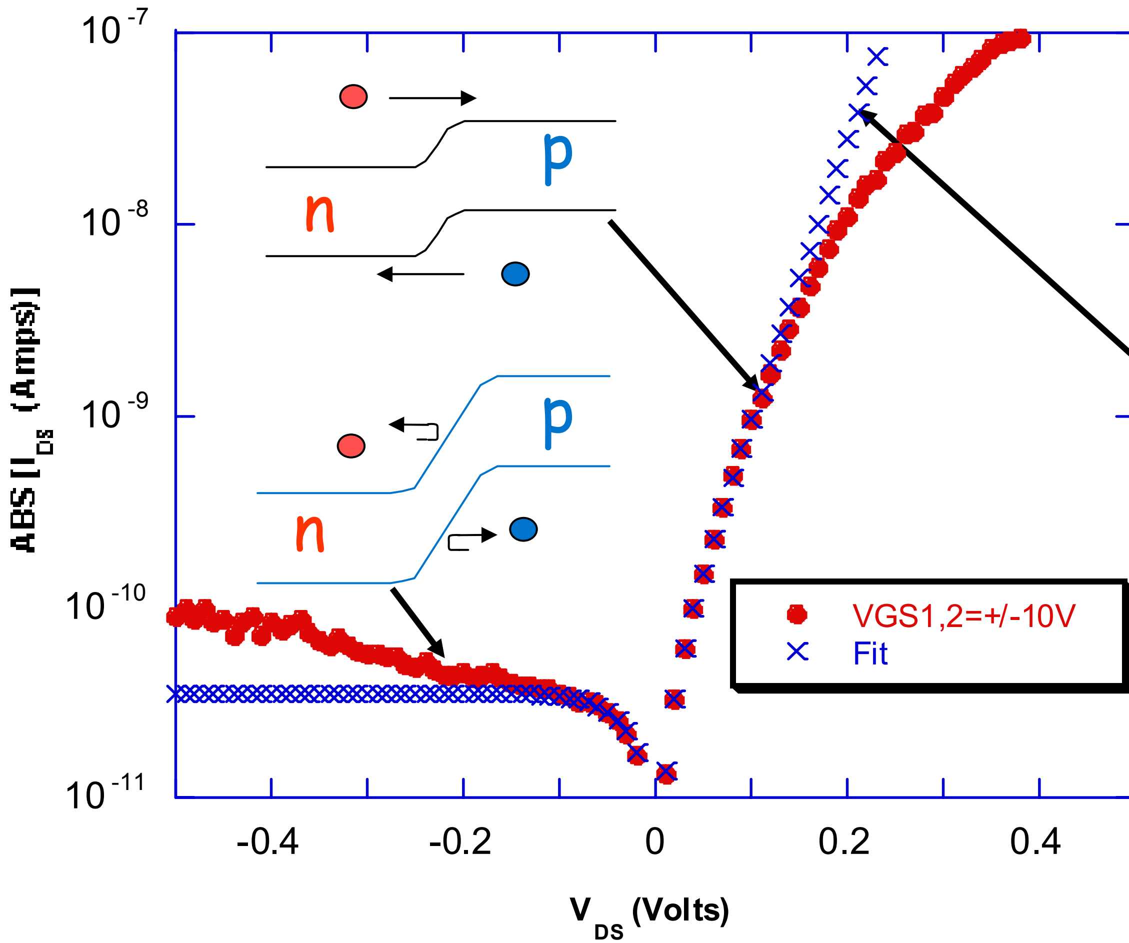
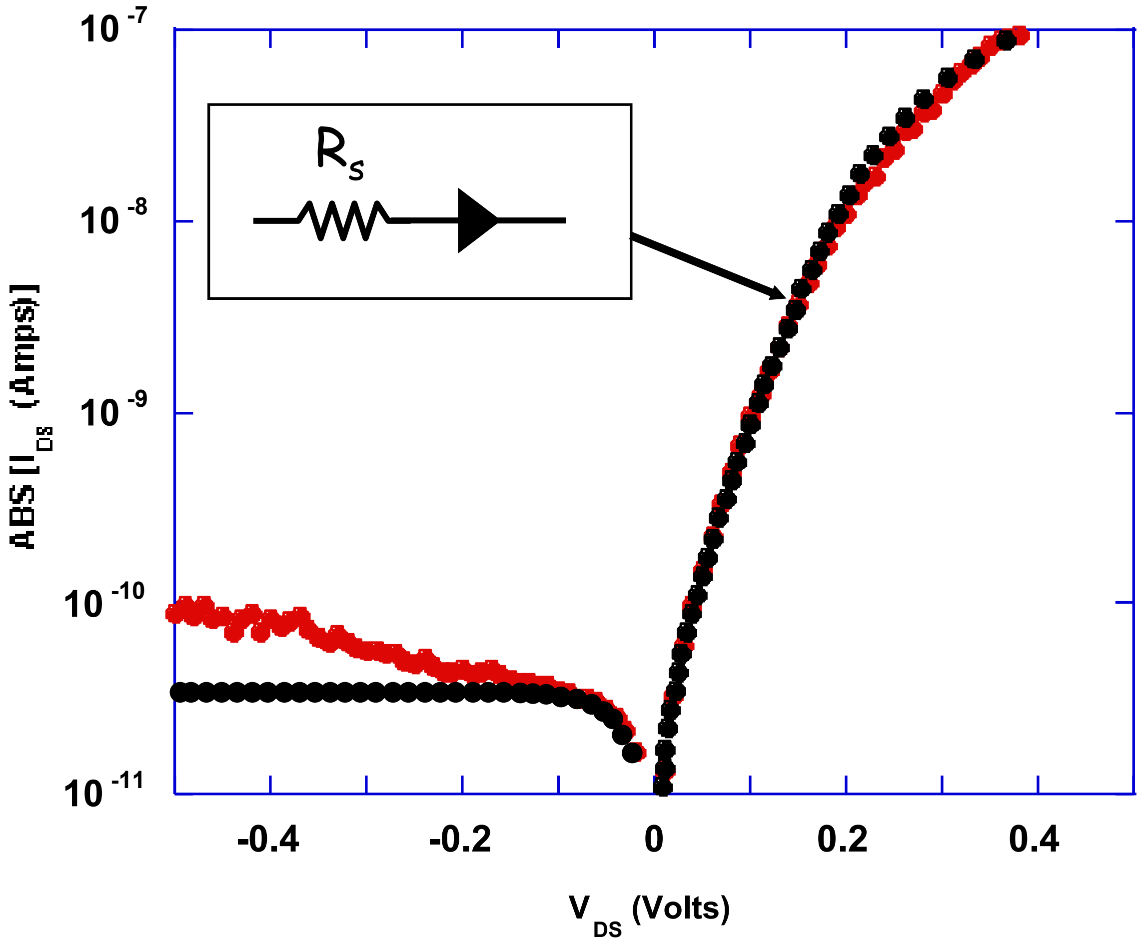
Nearly Ideal Diode Characteristics with n~1 (1.2)



$$I = I_o\left(e^{\frac{qV}{nK_BT}} - 1\right)$$

Series Resistance Limits Current:



Rs: measured from the resistive mode – due to n-type to metal contact resistance.

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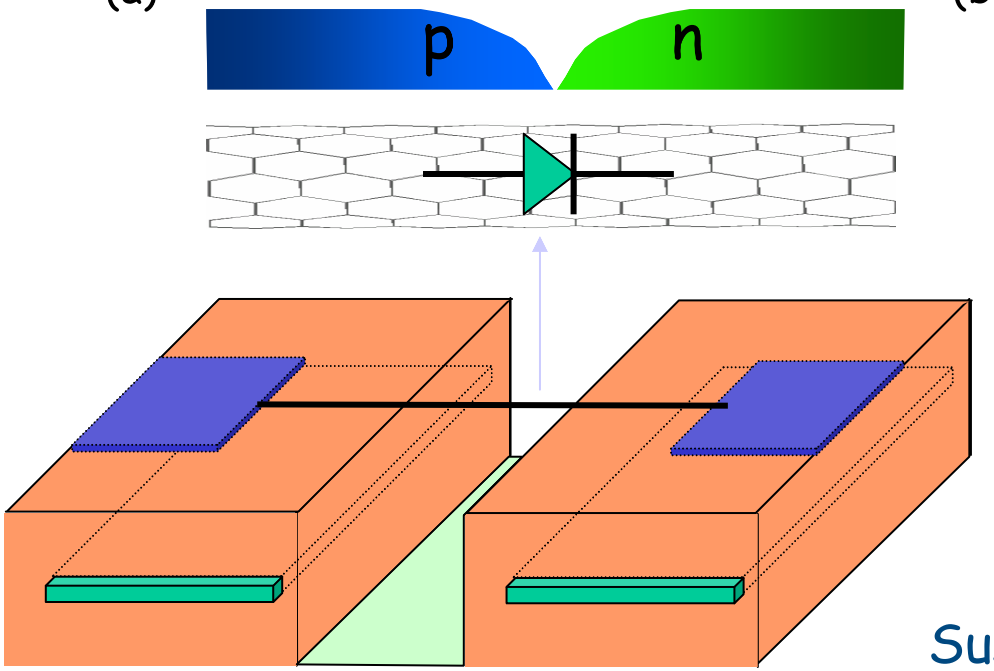
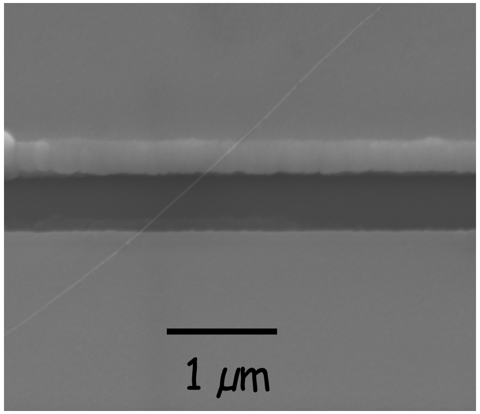
Suspended SWNT Diodes:

(a)

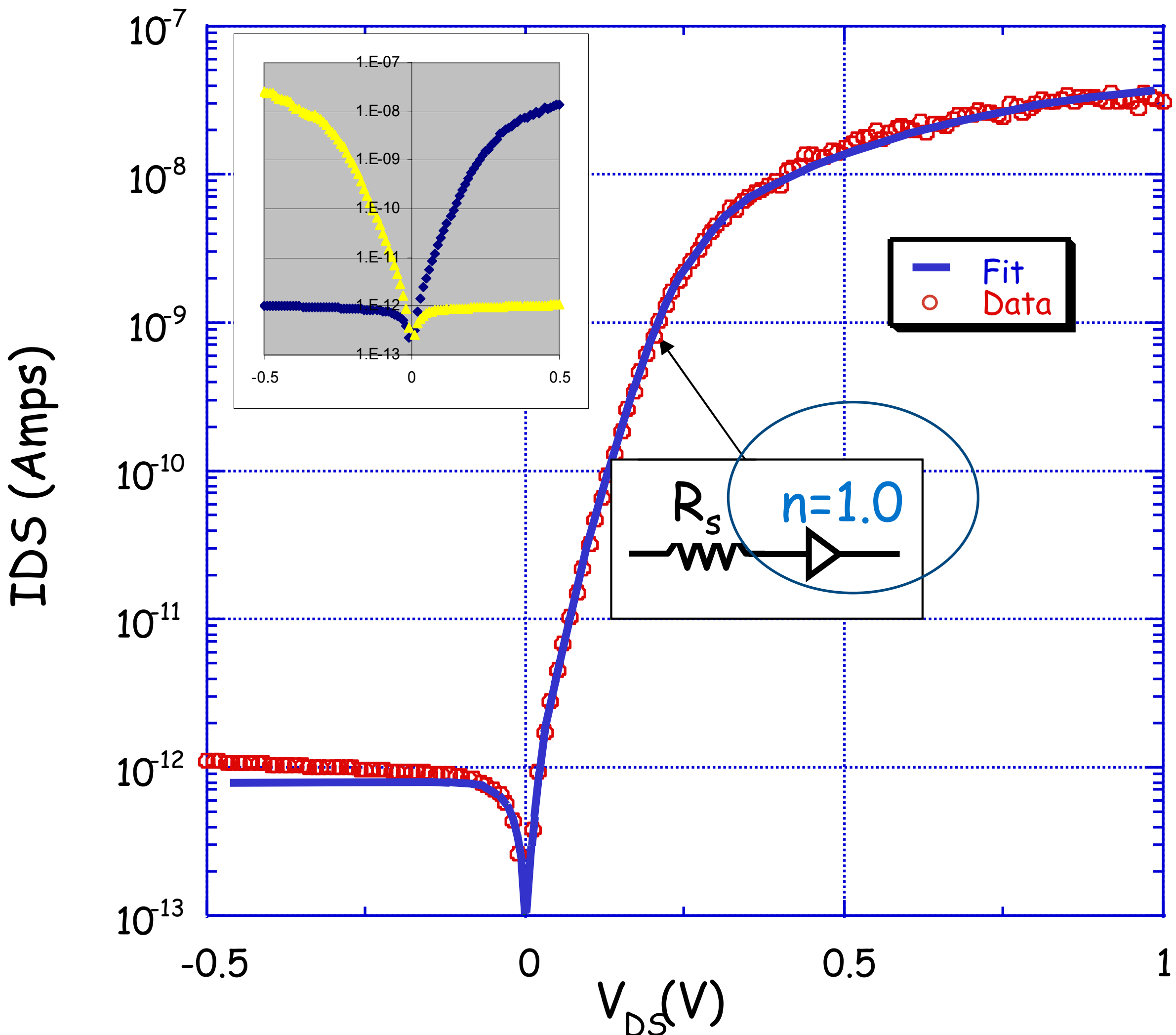


(b)



Suspended tube formed based on a self-registering technique

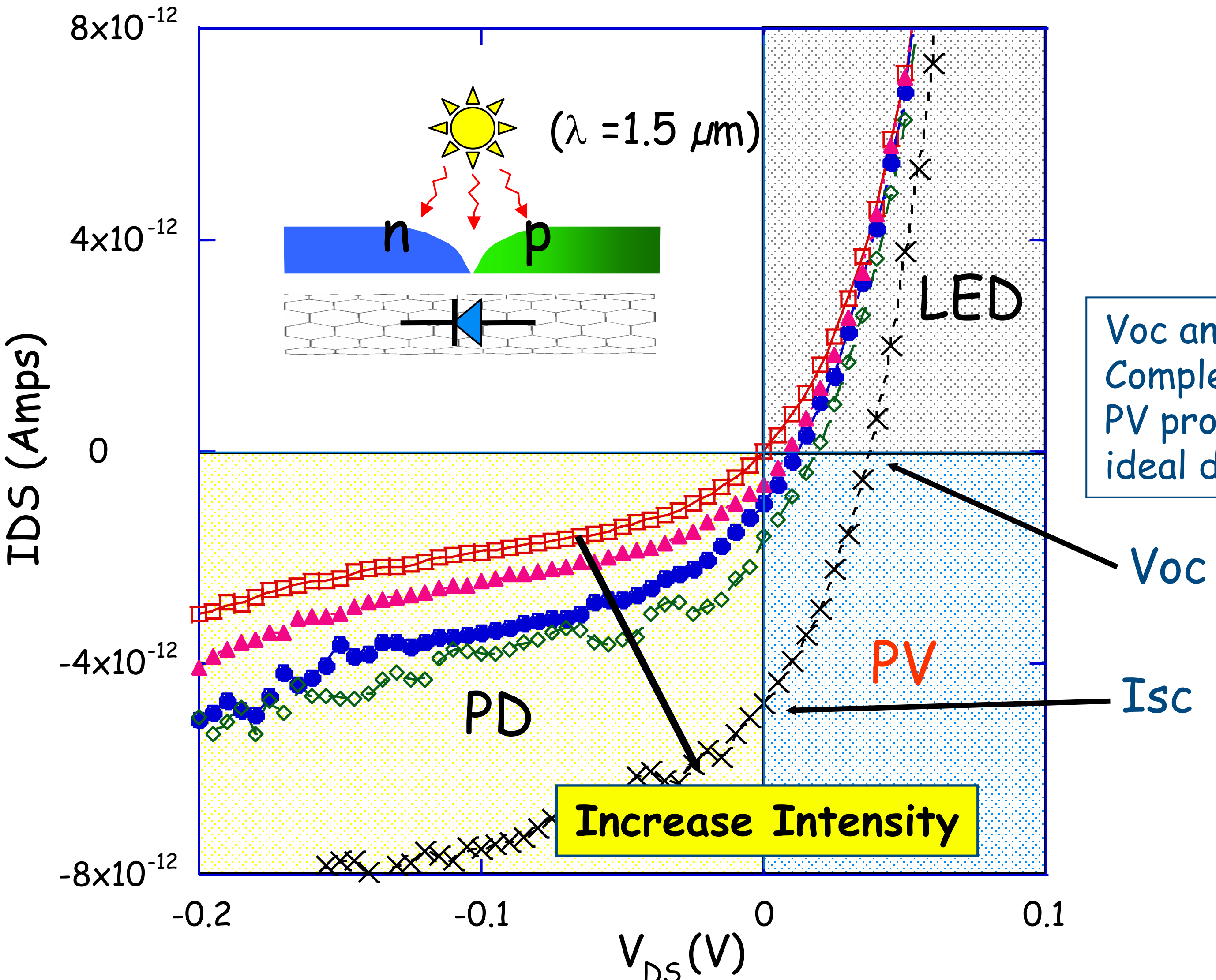
Ideal Diodes with Ideality Factor n=1.0 for Suspended Diodes



SWNTs are perfect, substrates are not.

J.U. Lee, Appl. Phys. Lett. 87, 073101 (2005)

Photovoltaic Effect

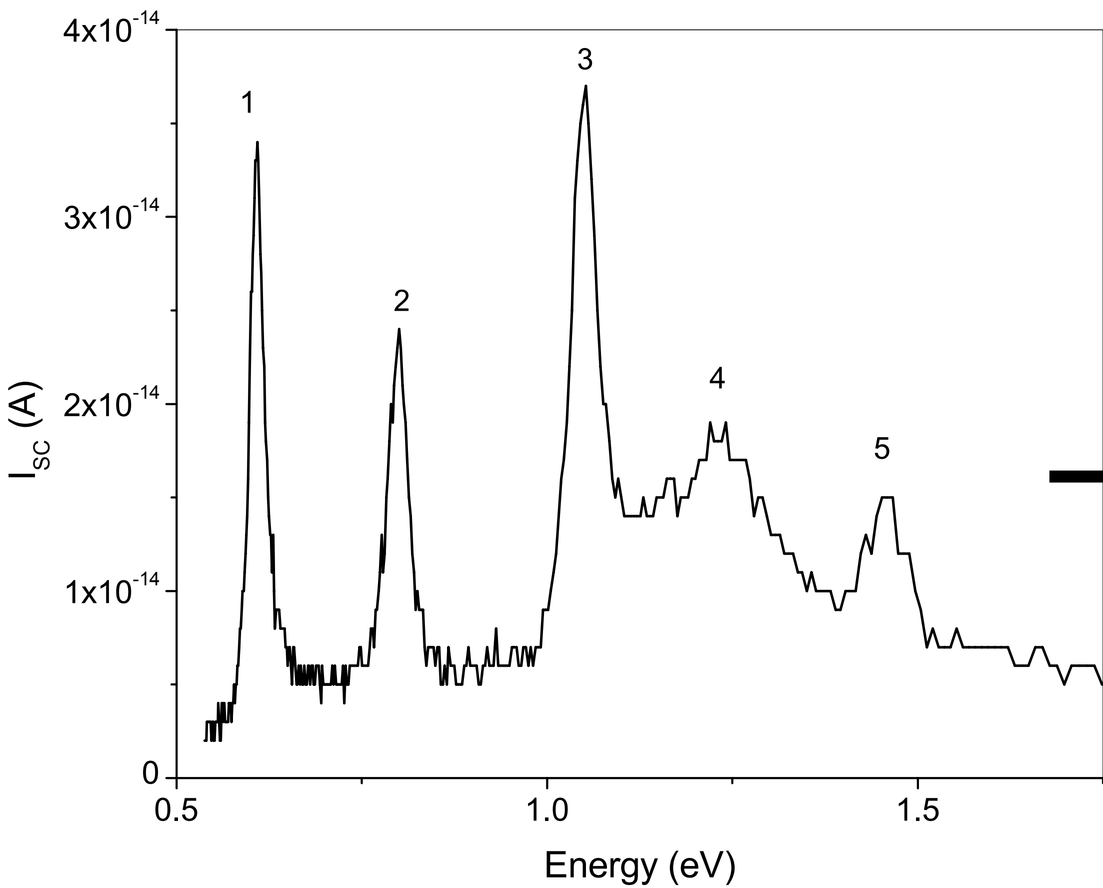


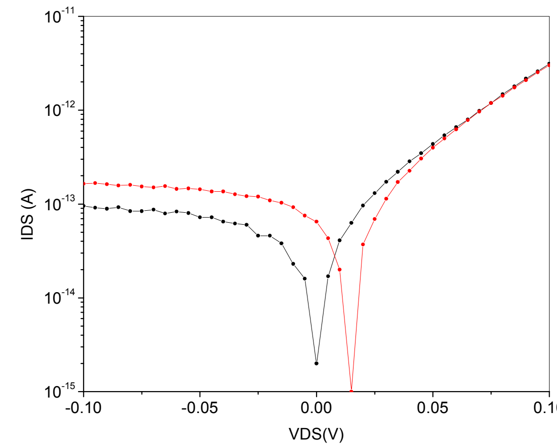
Voc and Isc: Completely define PV properties for an ideal diode

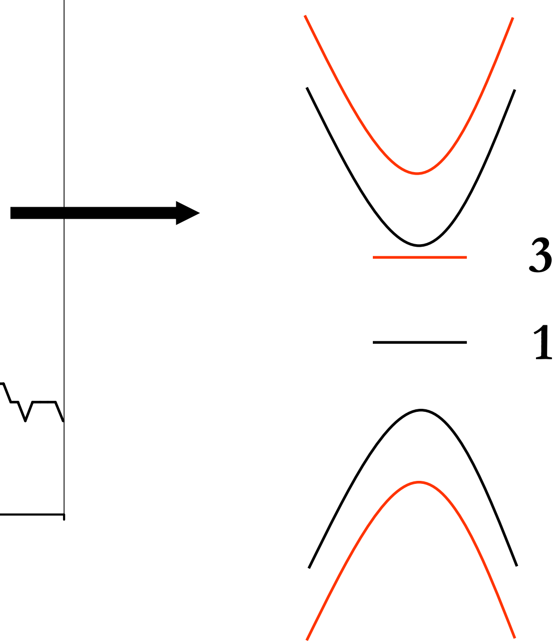
J.U. Lee, Appl. Phys. Lett. 87, 073101 (2005)

Exciton Peaks in the Photocurrent Spectra

(similar to SWNTs in solution)

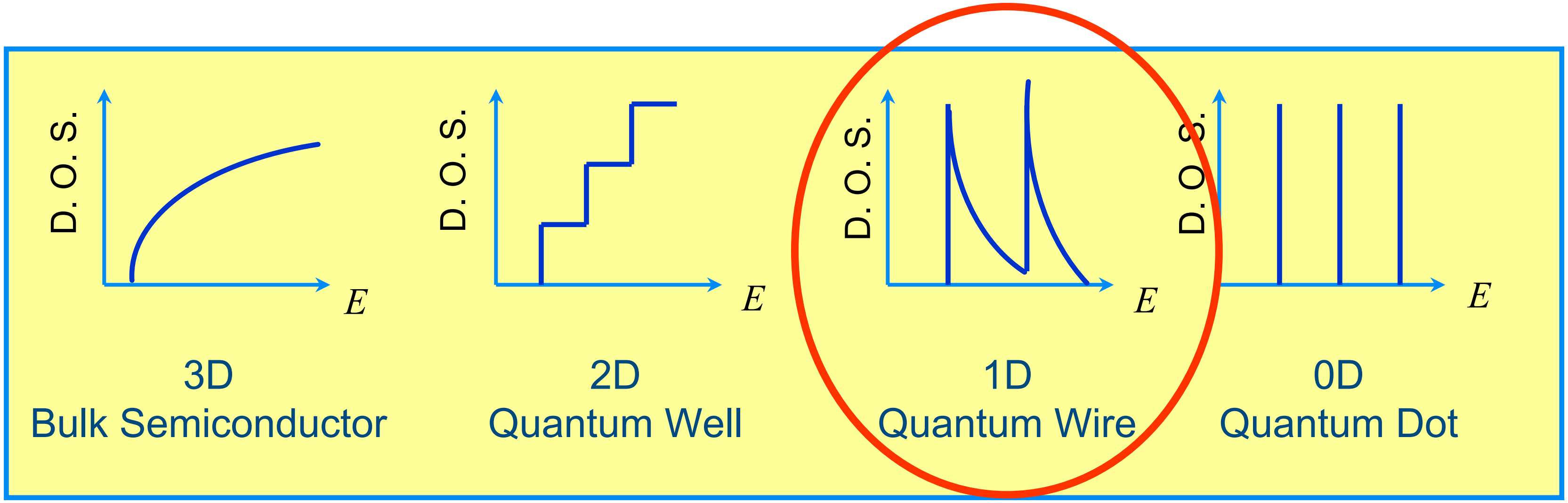




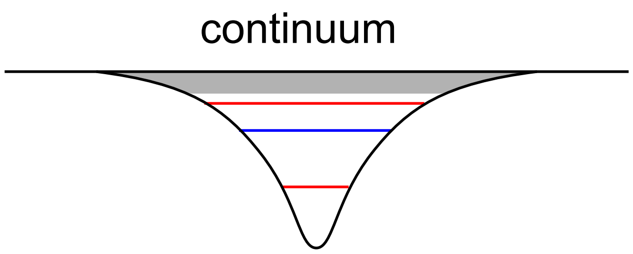


J.U. Lee et.al., Appl. Phys. Lett. 90, 053103 (2007)

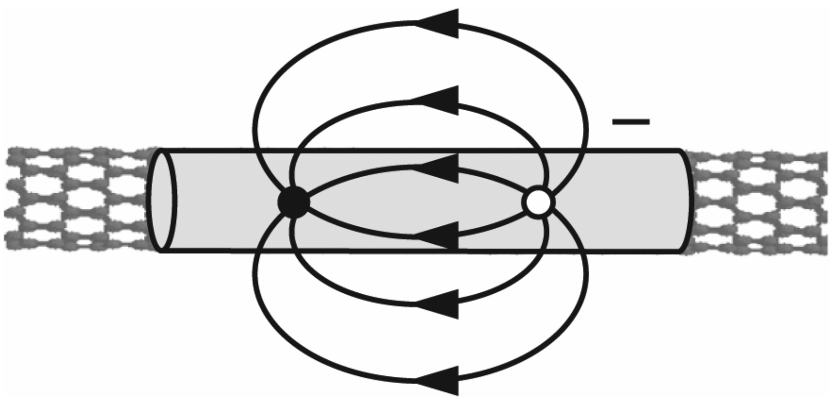
DOS: One Electron Model



EXCITONS IN CARBON NANOTUBES



Exciton Hydrogenic Levels
n=1,2,3…



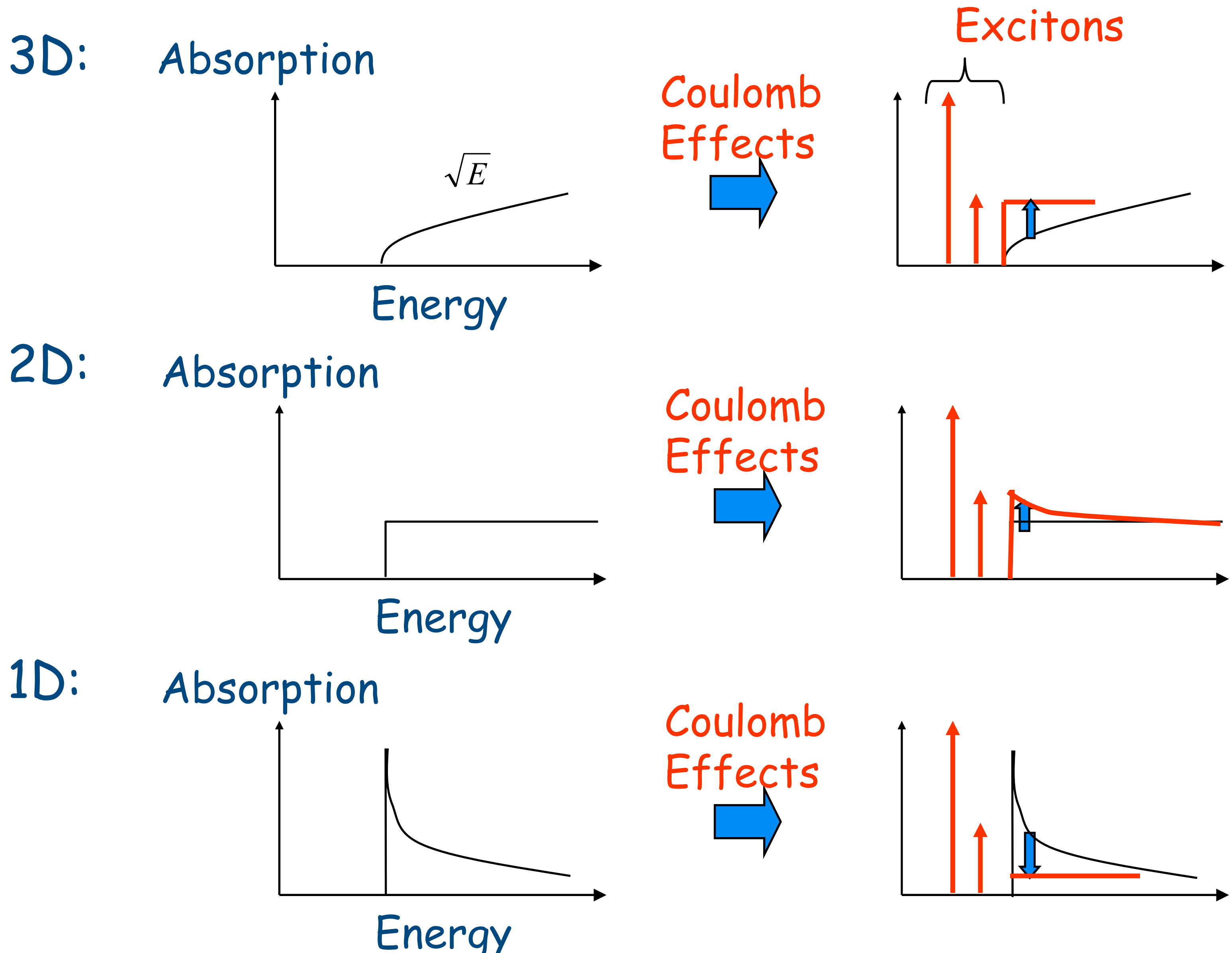
Electron-Hole Coulomb Interaction

$$H_{eh} = -\frac{e^2}{\varepsilon|\mathbf{r}_e - \mathbf{r}_h|}$$

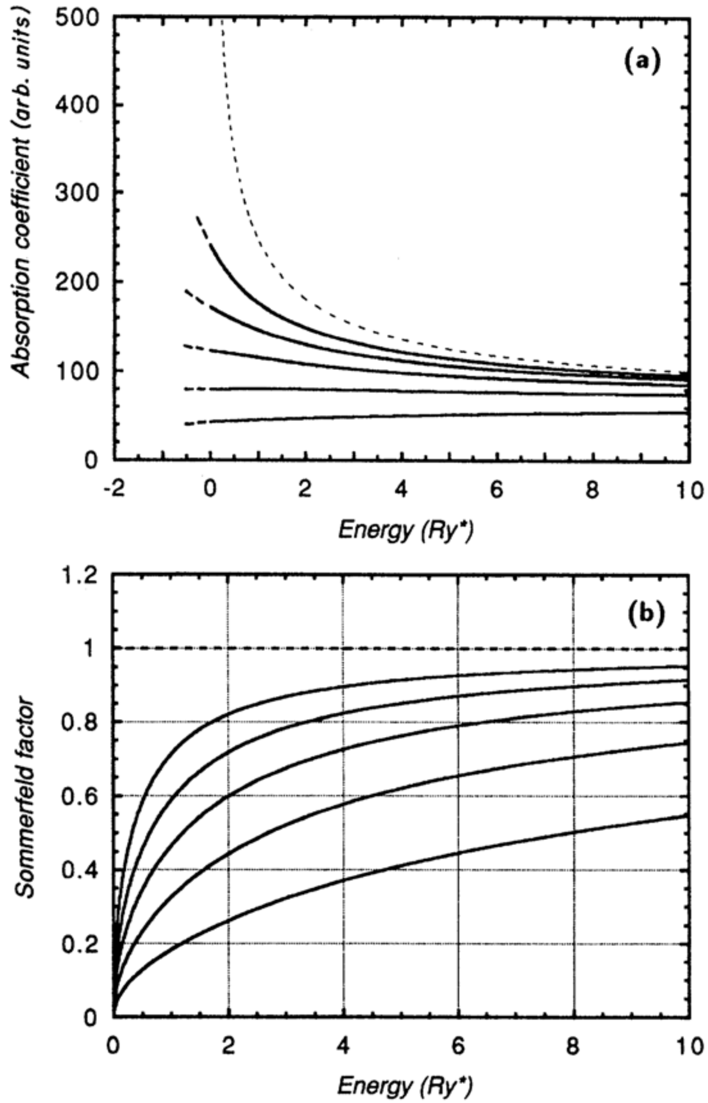
results in the electron-hole binding that forms the exciton states below the conduction subband edge

jlee1@uamail.albany.edu

Sommerfeld Factor: Coulomb Interaction

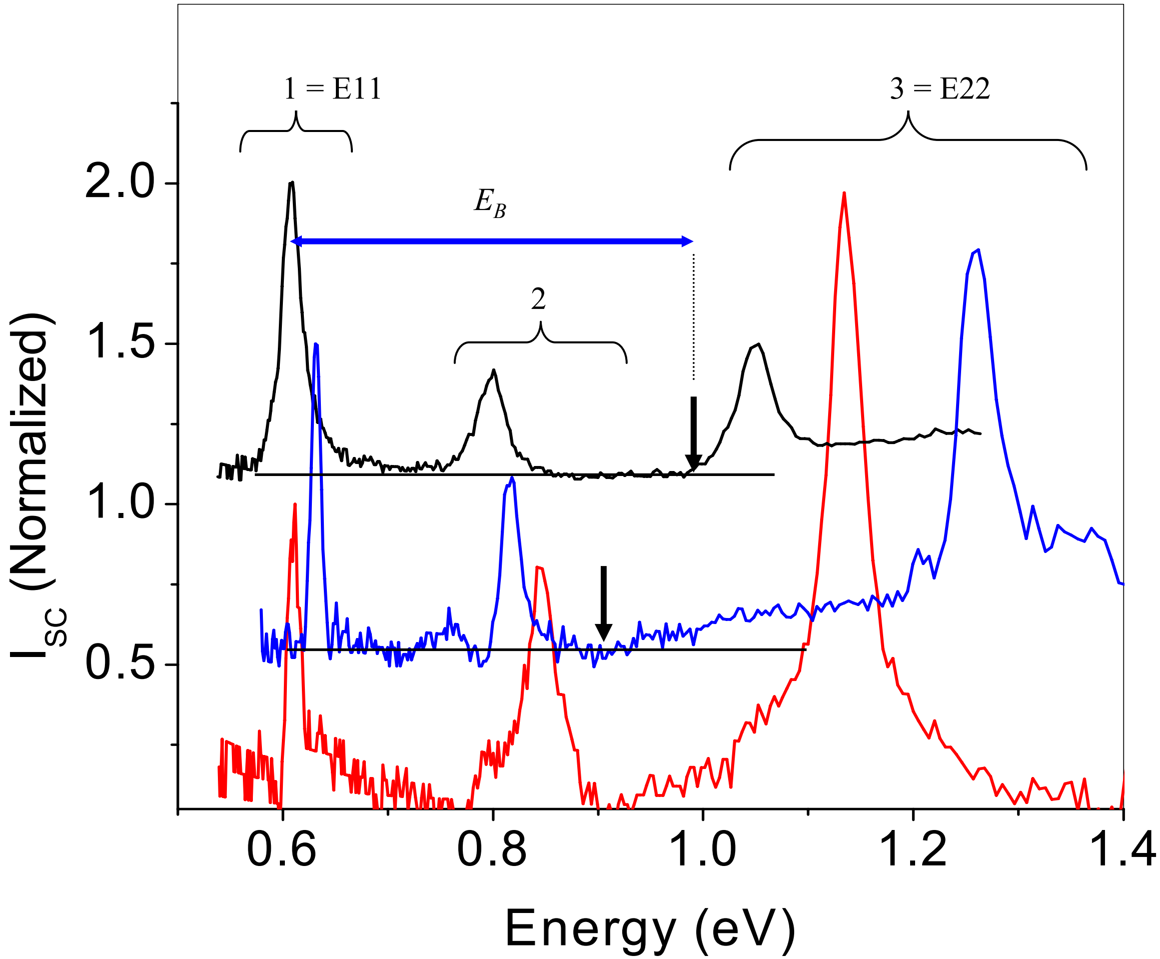


Sommerfeld Factor in 1D -> 0 at Eg



T. Ogawa and T. Takaghara, Phys. Rev. B 43, 14325 (1991)

Spectra with similar first energies

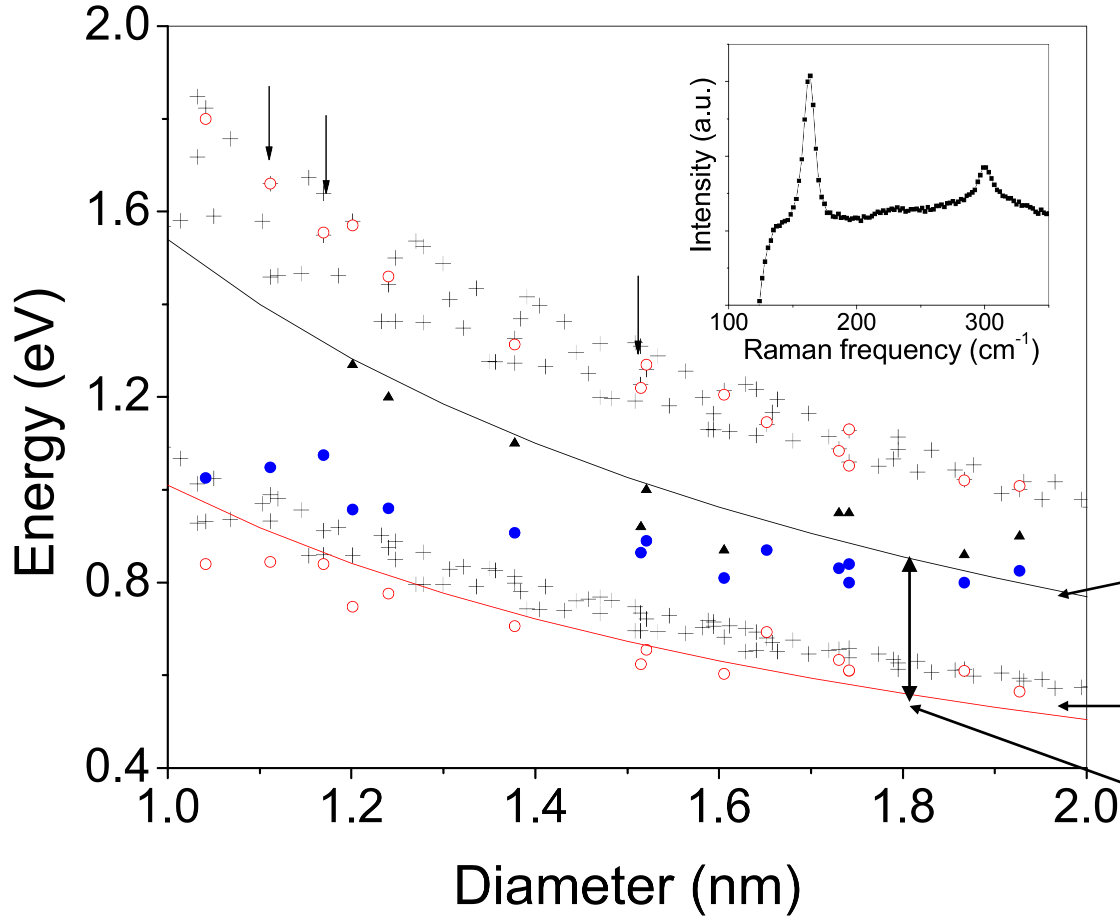


Lack of any features at Eg due to Sommerfeld factor <1

Side bands measure dark exciton

J.U. Lee et.al., Appl. Phys. Lett. 90, 053103 (2007)

Comparison to Photoluminescent Data:



+: Emperical Kataura
Weisman et.al. Nano Lett. 3, 1235 (2003)

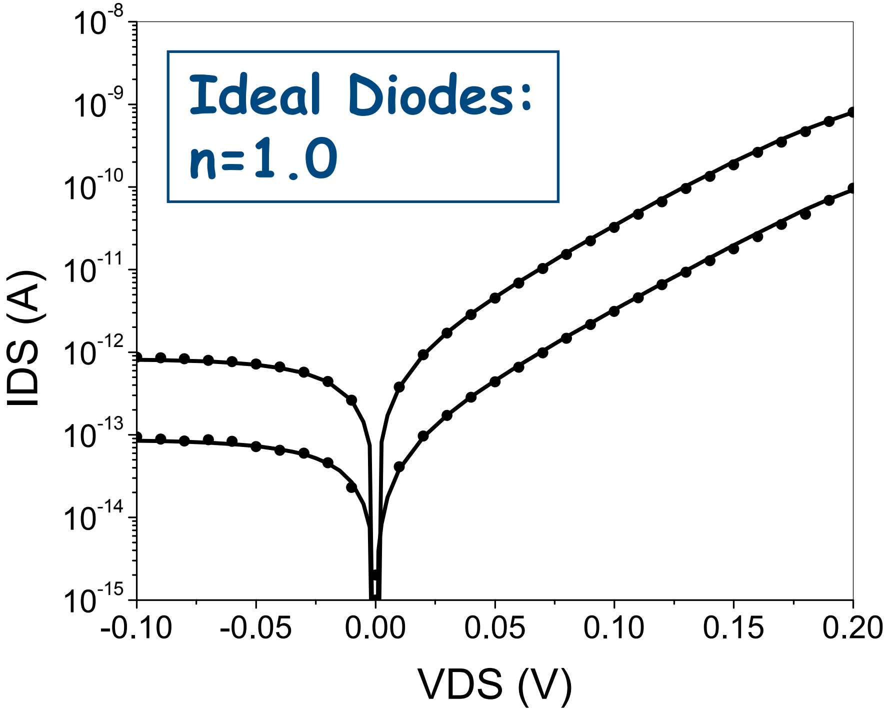
O- E_{11} and E_{22}
●- Exciton-phonon
▲ - Quasipaticle Bandgap

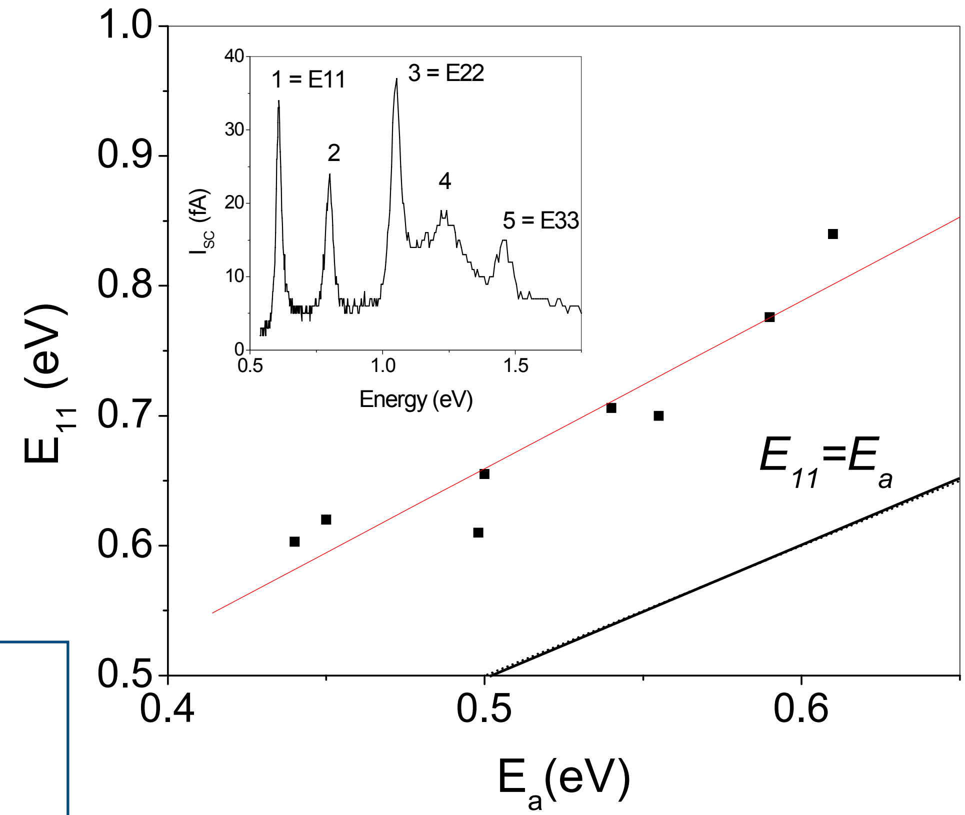
Continuum: 1.55eV/nm

E11: 1.01eV/nm

E_B: 0.54 eV/nm

Origin of the Ideal Diode Behavior and Exciton Dissociation:



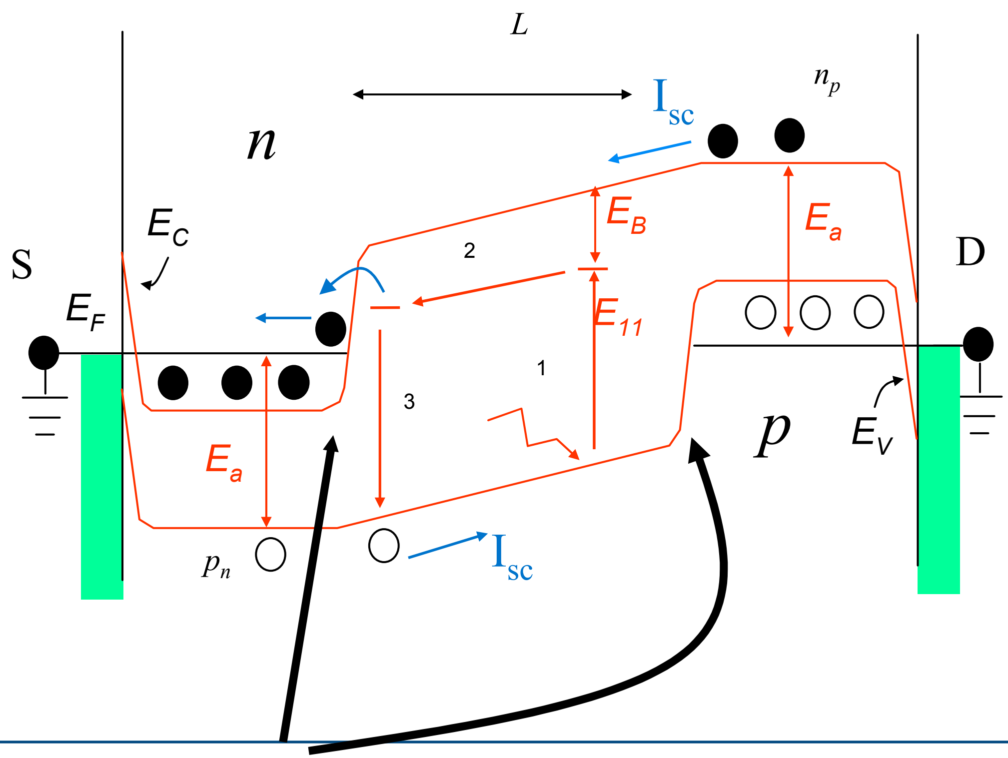


Two mechanism for n=1.0:

1) Direct Band-to-Band
2) Diffusion of Minority Carriers from the doped regions

Ea < E11 ??

Many-Body Renormalization of Band structure (BGR – band gap renormalization) and Proposed Mechanism for Exciton Dissociation:

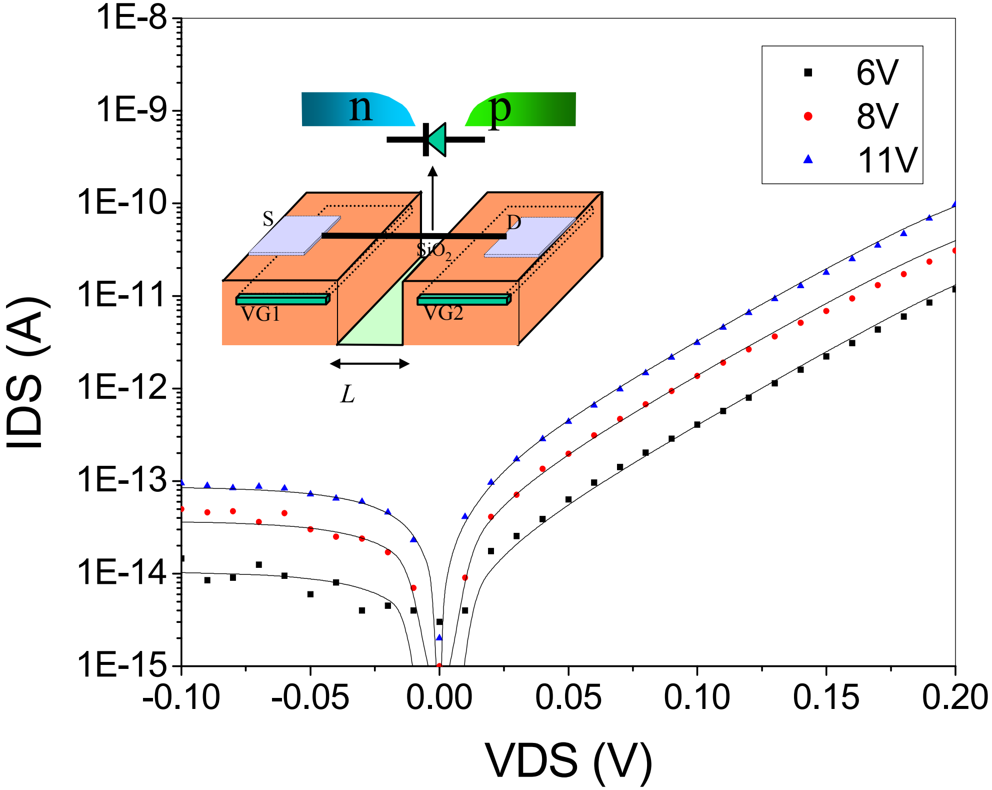


Formation of heterointerfaces along a homogenous material

J.U. Lee, Phys. Rev. B 75, 075409 (2007)

jlee1@uamail.albany.edu

Device Ideal for Studying BGR:



Variable Doping with VG1,2:

- Diode follows ideal relation with doping.

- Evidence of strong BGR: Io ↑ when Doping ↑.
 w/o BGR Io ↓ when Doping ↑.

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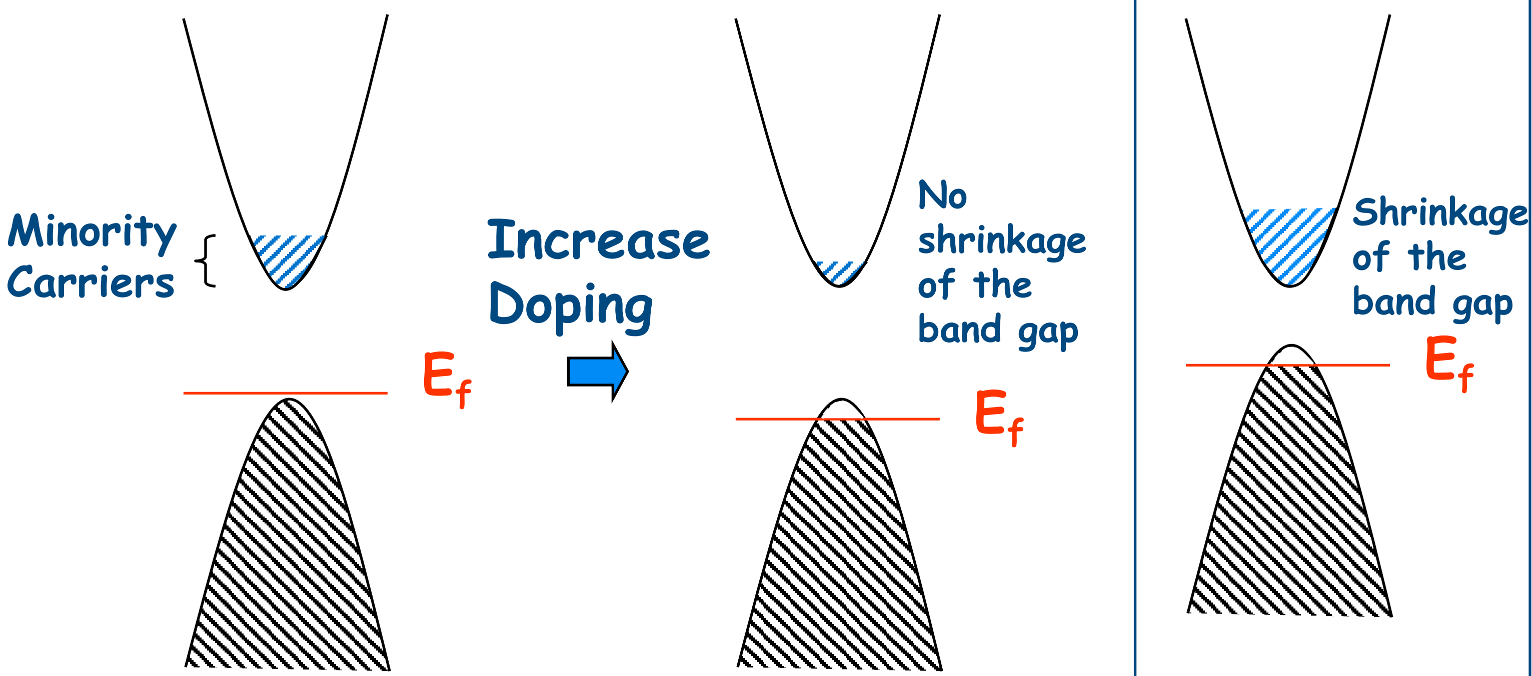
jlee1@uamail.albany.edu

Origin of increase in Io with Doping:



P type semiconductor

w/o BGR: minority carrier decreases

w/ BGR: minority carrier increases!

jlee1@uamail.albany.edu

Conclusions:

- Bipolar devices are more fun to study.
- How do neutral excitons dissociate to generate large photocurrents?
- Window to the study of many-body effects: BGR, biexctions, etc…

Funding: NSF, NRI/INDEX, IFC, IBM and UAlbany

jlee1@uamail.albany.edu

Future Work:
Graphene p-n junctions: Optics-like manipulation of electrons