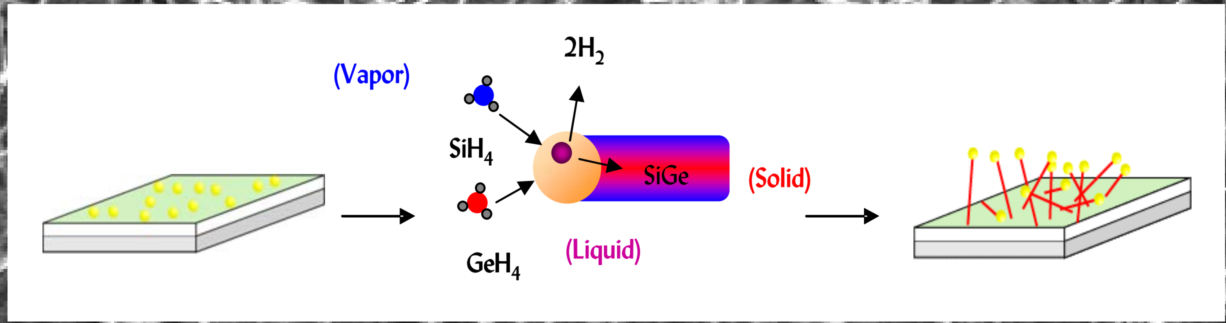
# Group IV Nano Optoelectronics:
## Recent Developments based on Bottom-Up Approaches

The 6th US-Korea Forums on Nanotechnology:
Nanoelectronics and its Integration with Applications

April 29. 2009

Moon-Ho Jo

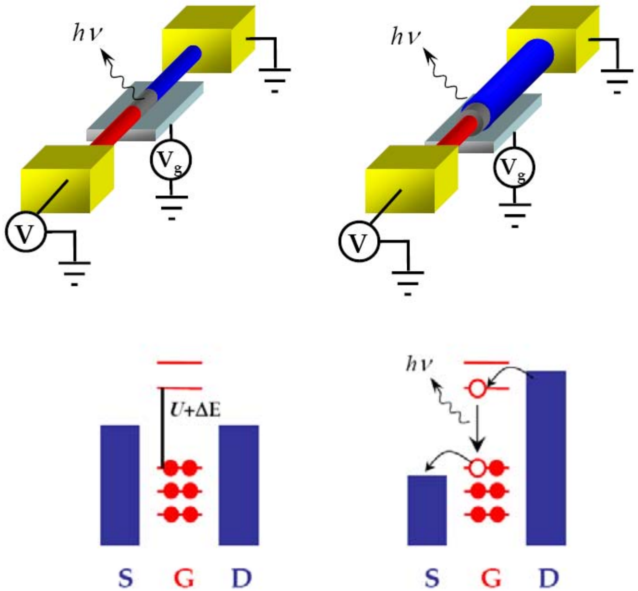
Dept. of Materials Science and Engineering
Pohang University of Science and Technology (POSTECH)

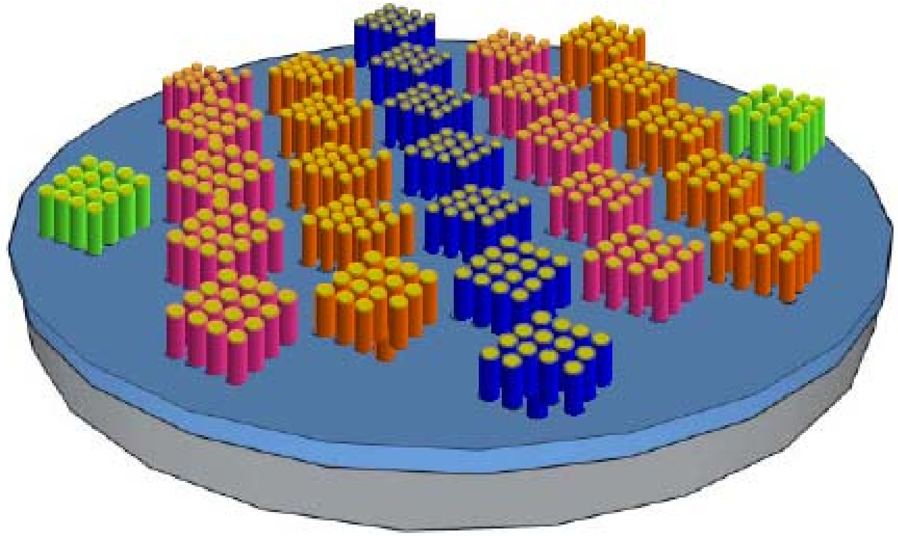



# Bottom-Up Nanowires for Integrated Nanosystems?

nanowire inside™

# Nanowire Photonics/Optoelectronics/Photovoltaics



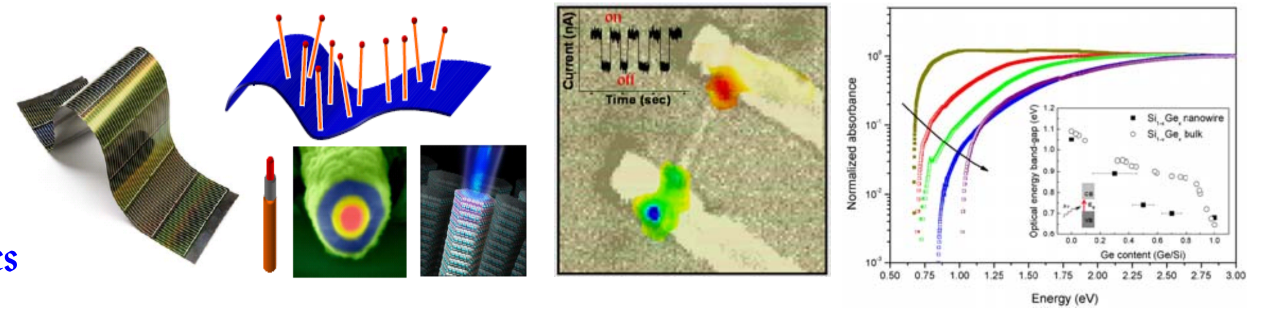



1. Unique size effects at the individual NW level

2. Large-area integrated NW arrays

## Nanowire Photonics/Optoelectronics/Plasmonics

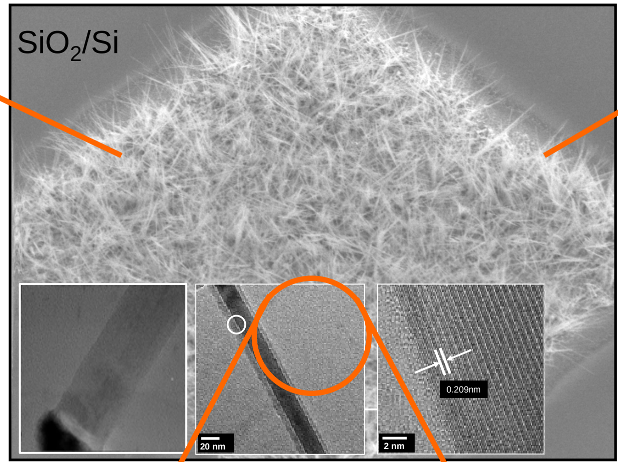
Nature Phys., Accepted (2009)
Nano Lett., Accepted (2009)
Appl. Phys. Lett., In Press (2009)
Appl. Phys. Lett., 92 263111 (2008)
Nano Lett. 6 2679 (2006)





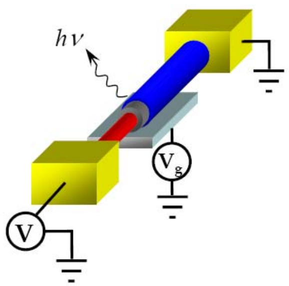
## Nanowire Growth

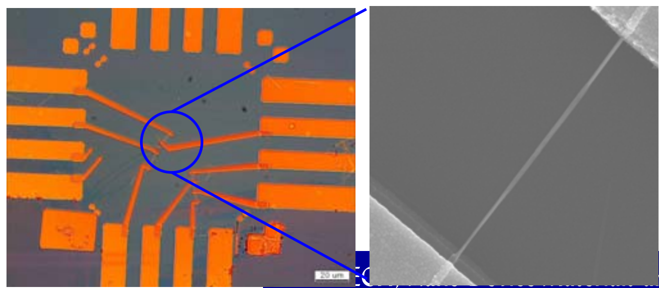
Submitted, (2009)
Nano Lett. 8 431 (2008)
Adv. Mater. 20 4684 (2008)
Chem. Mater 20 6577 (2008)
Appl. Phys. Lett., 91, 223107 (2007)
Adv. Mater., 19, 3637 (2007)
Appl. Phys. Lett. 88, 193105 (2006)
Nano Lett. 4 1547 (2004)



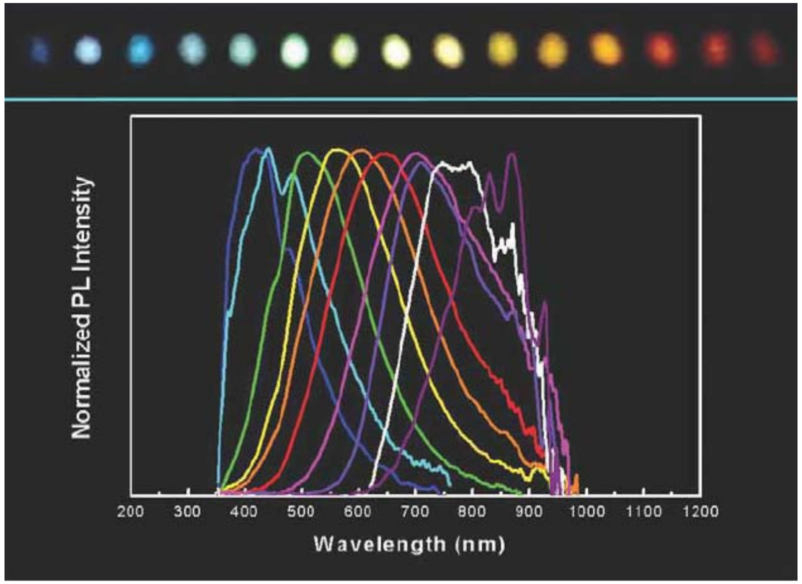

## Nanowire Electronics

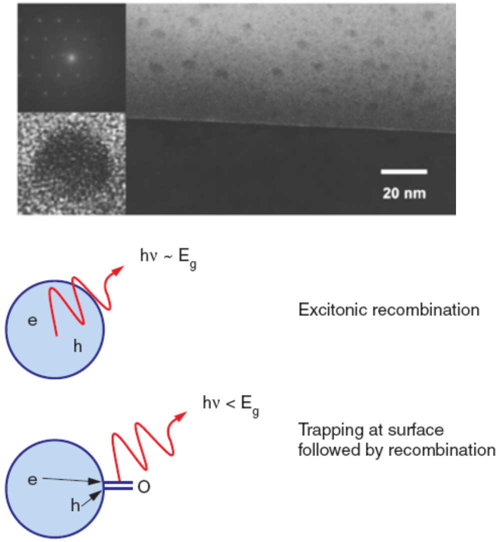
Nano Lett. 8 4523 (2008)
Appl. Phys. Lett., 91, 033104 (2007)
Nano Lett, 6 2014 (2006)



# Si Quantum Dot Photonics



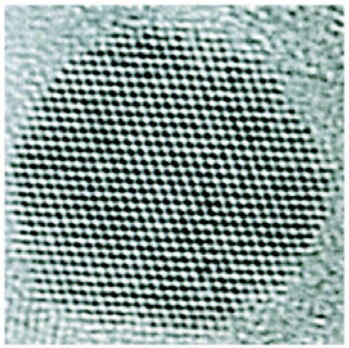



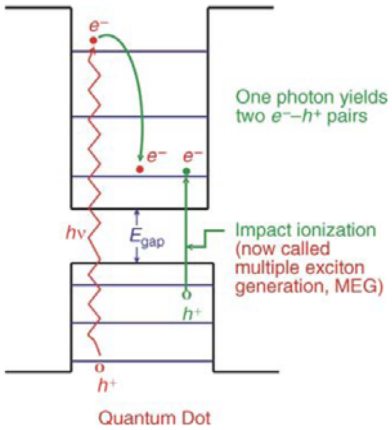

Photoluminescence in NIR to UV from Si quantum dots (QD) of various size*

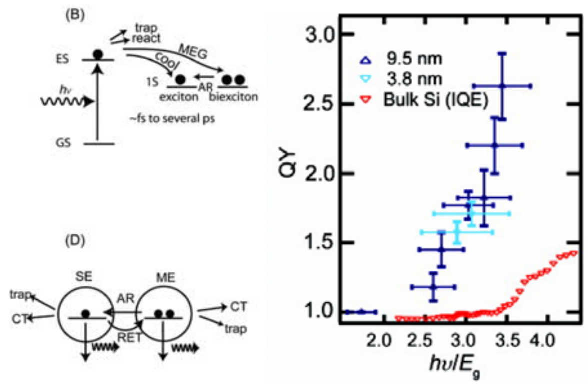
T.Y. Kim et al., *Appl. Phys. Lett.* 85, 5355 (2004)
Lorenzo Pavesi and David J. Lockwood, *Materials Today*, Jan. 26, 2005

- Exciton-Bohr radius of Si is ~5nm. (~18nm for Ge)
- Because of (possible) quantum confinements, Si QDs smaller than 5nm, can emit light from the near infrared throughout the visible with quantum efficiencies in excess of 10%.
- Radiative transition rates increase due to the confinement of *e-h* pairs.

# Multiple Exciton Generation in Si Quantum Dots





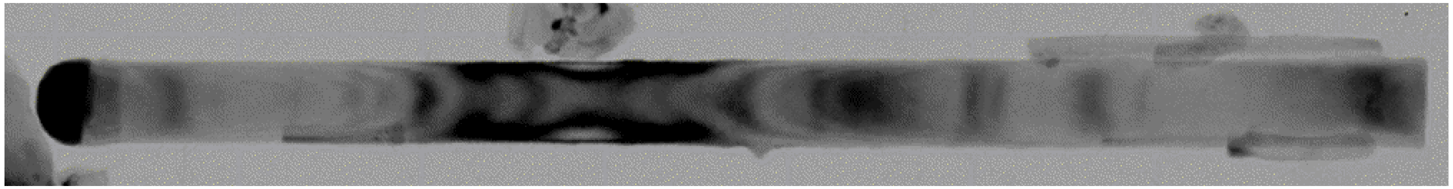



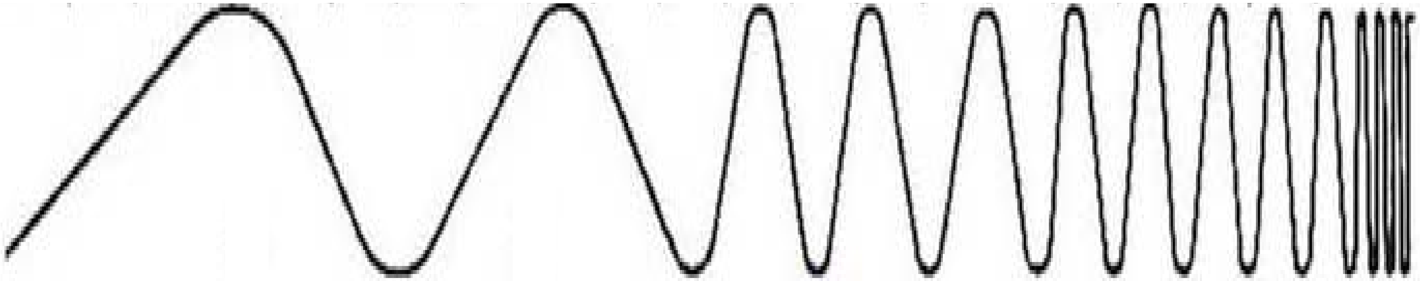

M.C. Beard, *Nano. Lett.* 7, 2506 (2007)

• Multiple bound *e-h* pairs (excitons) can be generated in Si nanocrystals (9.5 nm) upon photon absorption of energy greater than twice the band gap.

• The exciton production quantum was found to be 2.6 excitons per absorbed photon at $3.4E_g$.

# Si:Ge Nanowire Optoelectronics





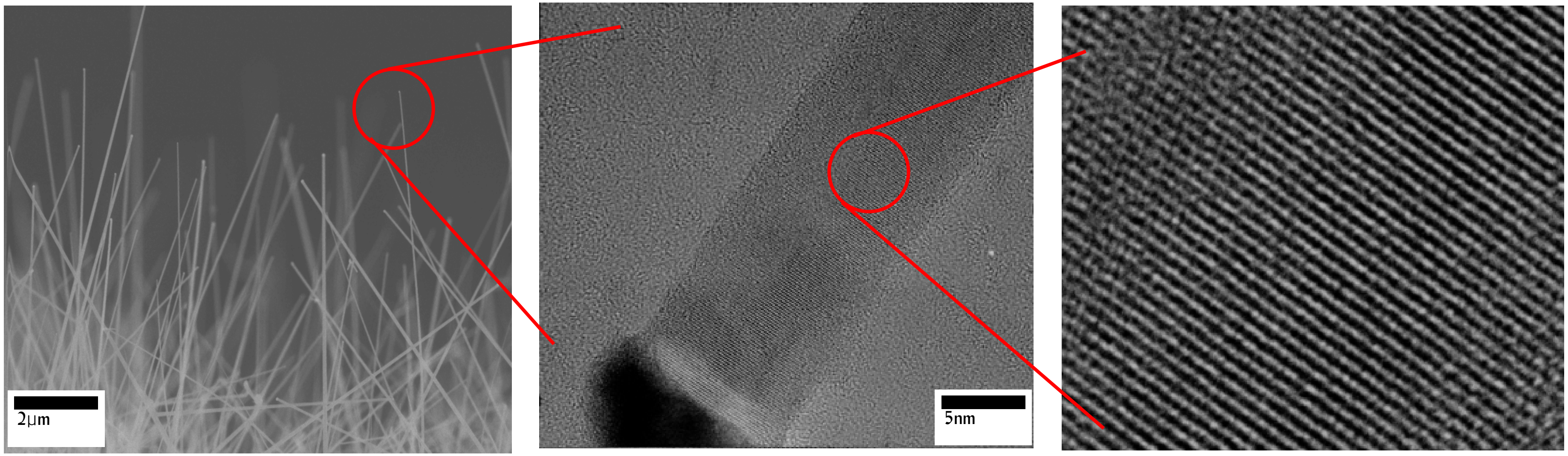
Si:Ge Nano Crystals: The model system for continuously varying lattices and energy band-gaps at the nanometer scale

1. Nanowires: Electrically driven Efficient Light-Emitting/Detecting Devices

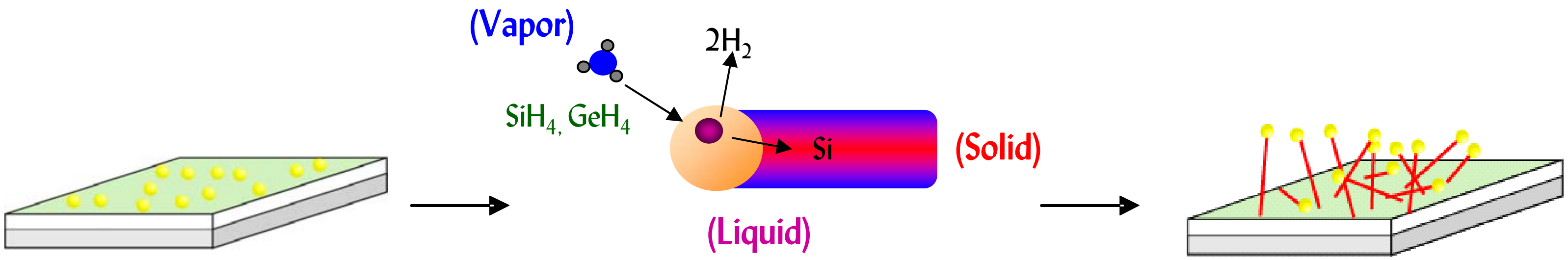
2. Si:Ge Alloys: Tunable Energy upon Light-Matter Interaction

# Vapor-Liquid-Solid (VLS) Nanowire Growth

## Conventional VLS-CVD Nanowire Growth

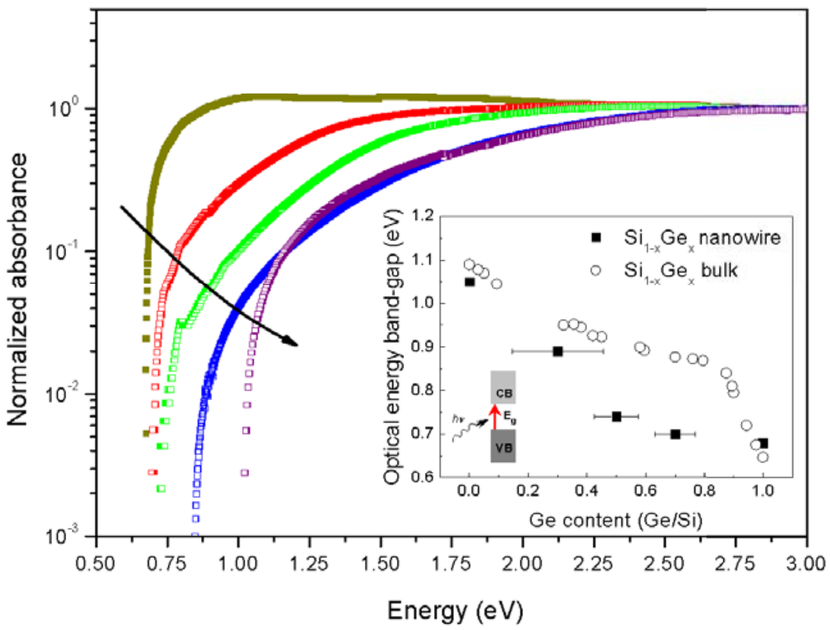


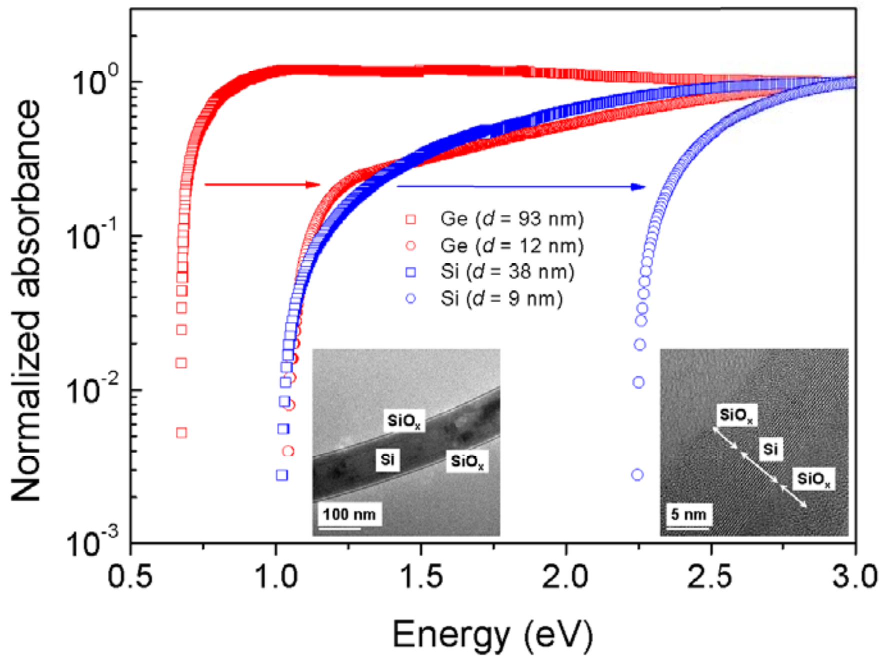

Chang-Beom Jin et al., *Appl. Phys. Lett.* **88**, 193105 (2006)
Jee-Eun Yang, et al., *Nano Lett.* **6**, 2679 (2006)



# $Si_{1-x}Ge_x$ Nanowire Crystals: Optical Band-Edge Absorption

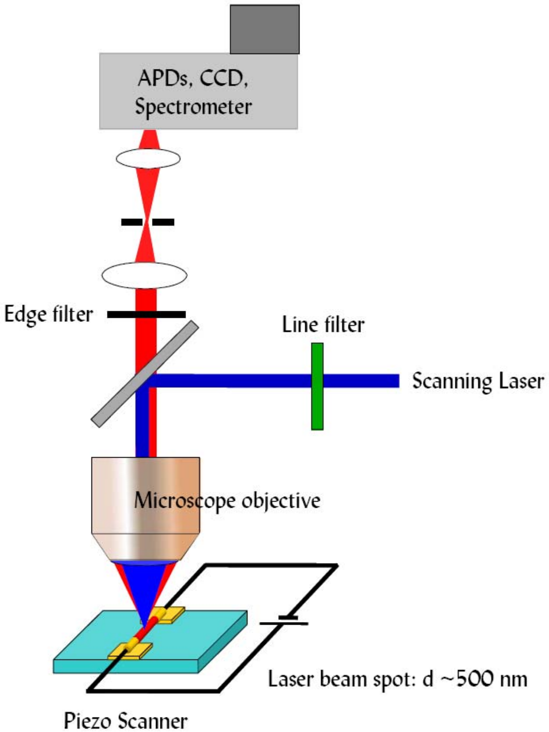
Jee-Eun Yang et al., *Nano Lett.* **6**, 2679 (2006)

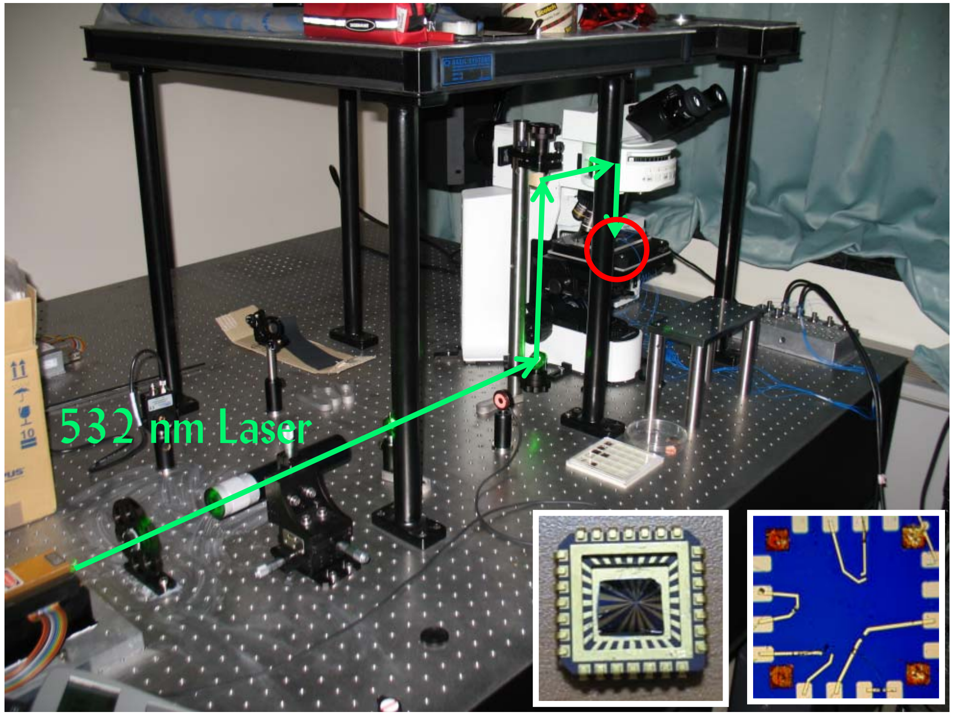



- The optical band-edge of 0.68eV and 1.05eV for Ge and Si nanowires, and these values agree with the energy band-gaps of bulk Ge and Si crystals of 0.65eV and 1.12eV.
- The optical band-edge in various $Si_{1-x}Ge_x$ nanowires systematically shifts from that of Si nanowires to that of Ge nanowires with increasing Ge content.
- We observed strong blue-shift of optical band-edge for thinner nanowires whose diameter is smaller than 10nm. (Exciton-Bohr radius of 4.7nm for Si and 17.7nm for Ge)

# Spatially Resolved Optoelectronic Measurements



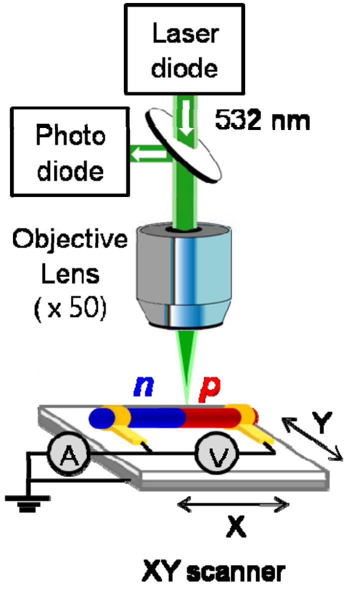




Diffraction limit : $\Delta R = k \times \frac{\lambda}{N.A.}$ = 360 nm, 650 nm

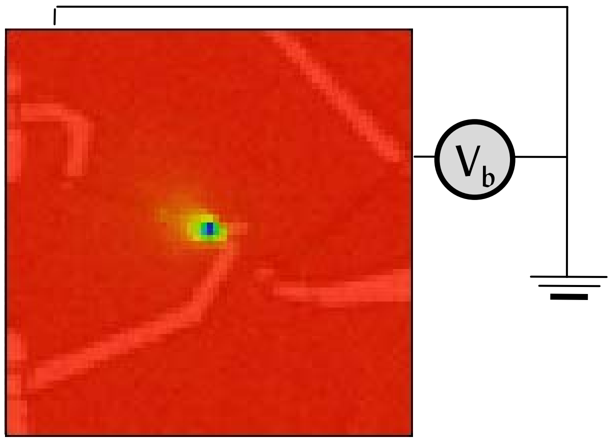
$k$ : technical constant (~0.61)
N. A. : numerical aperture (0.5, 0.9)

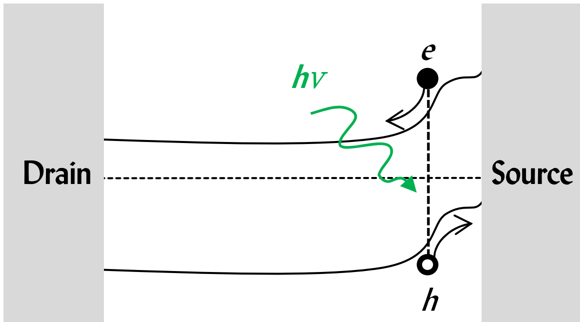
- A new experimental setup based on a scanned laser confocal microscope allows combined measurements of "spatially resolved" electroluminescence and photoconductivity.
- The setup also allows the "spectral measurements" of electroluminescence and correlated photon counting.
- With the addition of an ultrafast laser, it should also allow "time-resolved measurements".

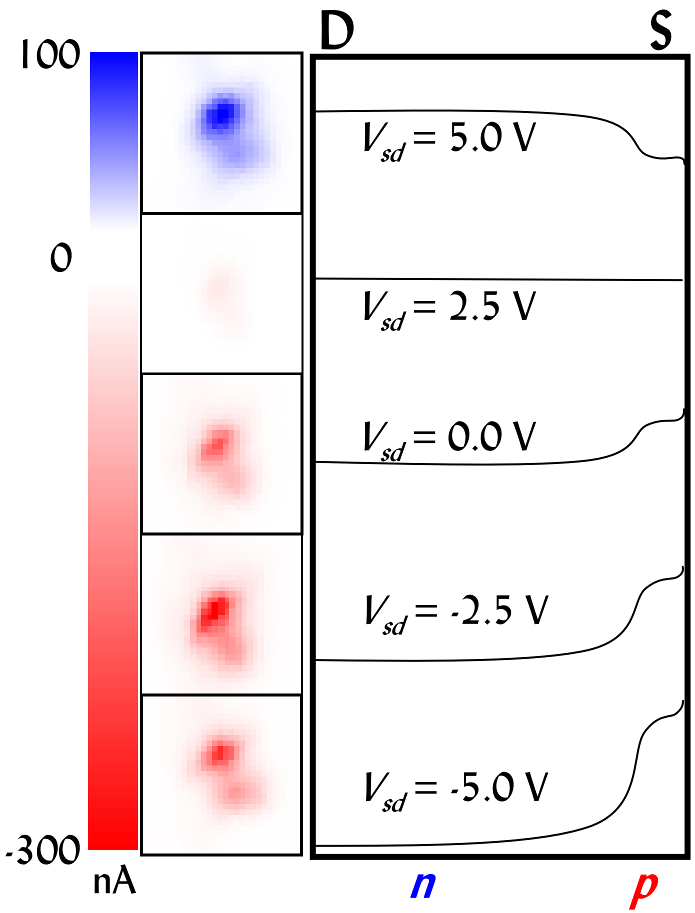
Intra-Nanowire *p-n* diode




# Photocurrent in Si Nanowire *p-n* diode

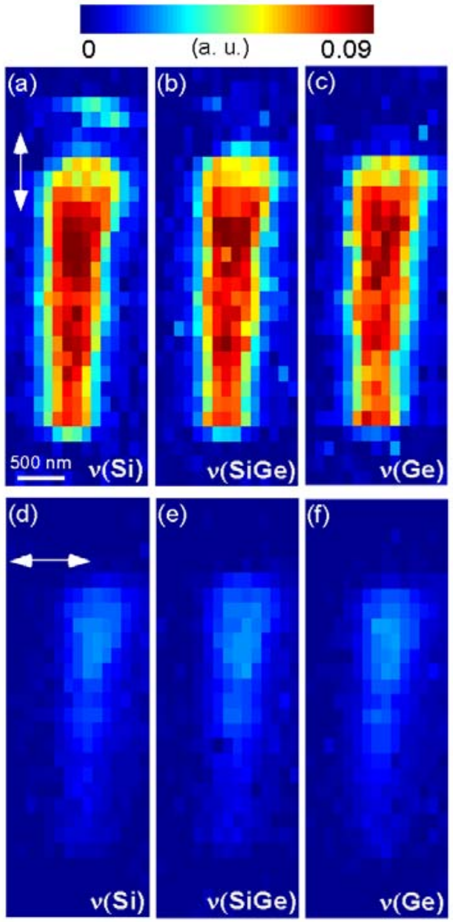


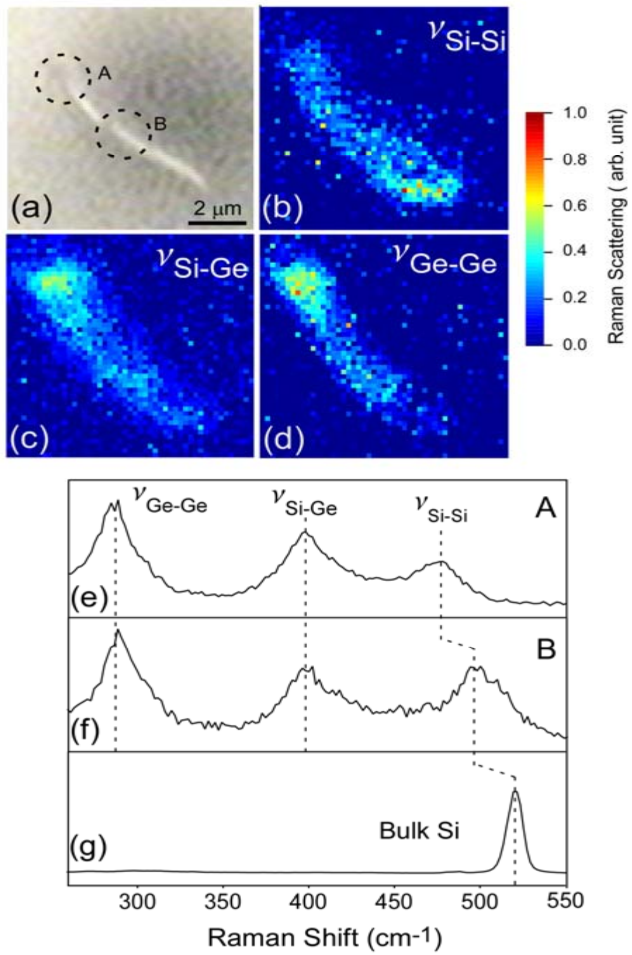




Cheol-Joo Kim et al., *Nano Lett.*, Accepted (2009)

# Confocal Raman Spectro-Microscopy

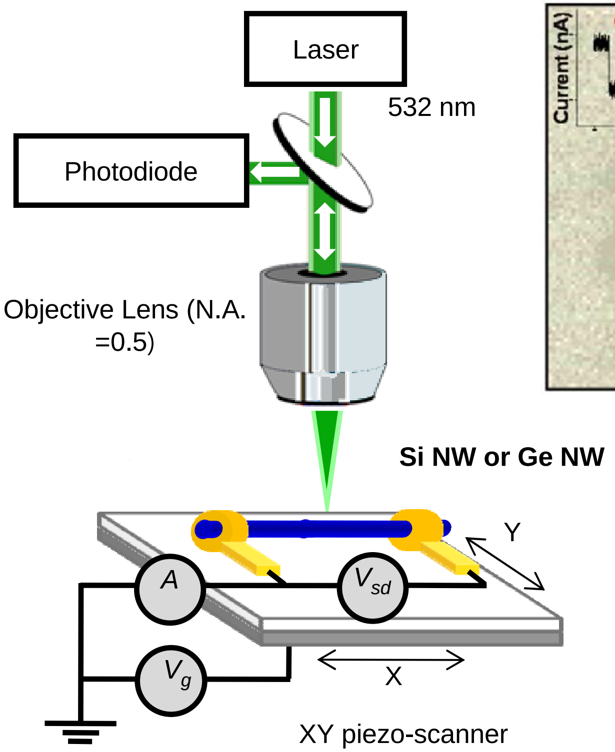


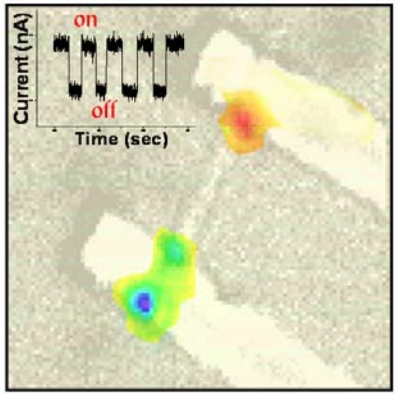



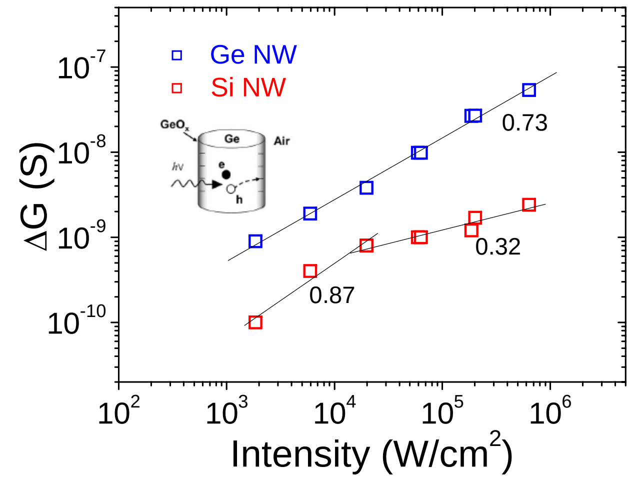

Jee-Eun Yang et al., *Appl. Phys. Lett.*, **92**, 263111 (2008)
(with Prof. Zee Hwan Kim, Korea Univ. )

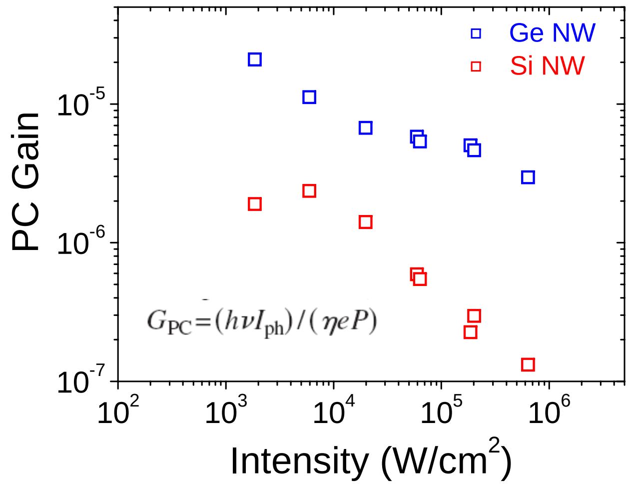
## Ge Nanowire Photodetector

Cheol-Joo Kim et al., *Nano Lett.*, Accepted (2009)



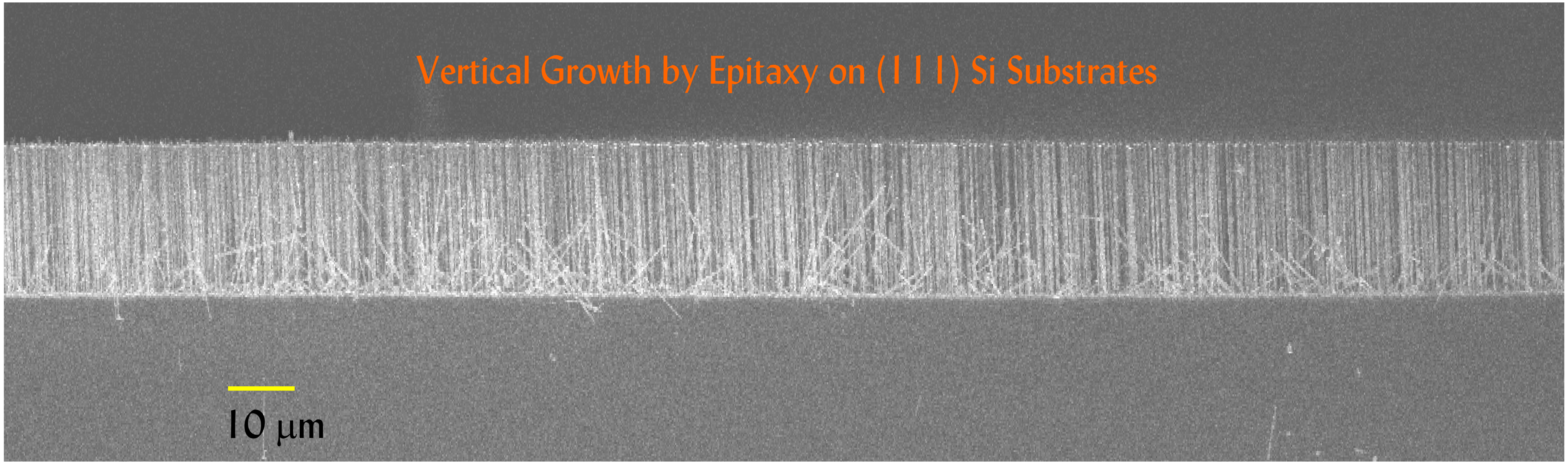



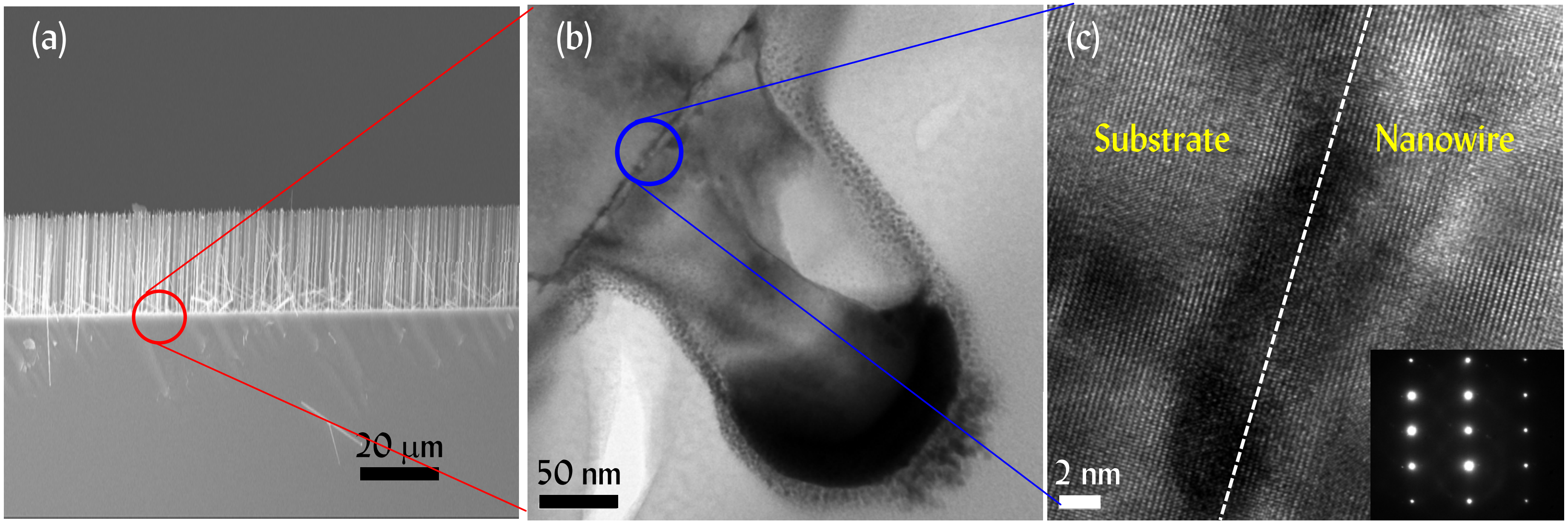




- The PC for Ge NWs is more than two orders of magnitude higher than that of Si NWs. This PC enhancement in Ge NWs is even more pronounced at lower light intensity.
- Ge NW can be an excellent candidate for polarization-sensitive nanoscale photodetectors especially in the visible range.
- Ge NWs show extremely sensitive photoresponse especially at a low intensity regime, which is attributed to the internal gain mechanism, originating from the surface state filling.

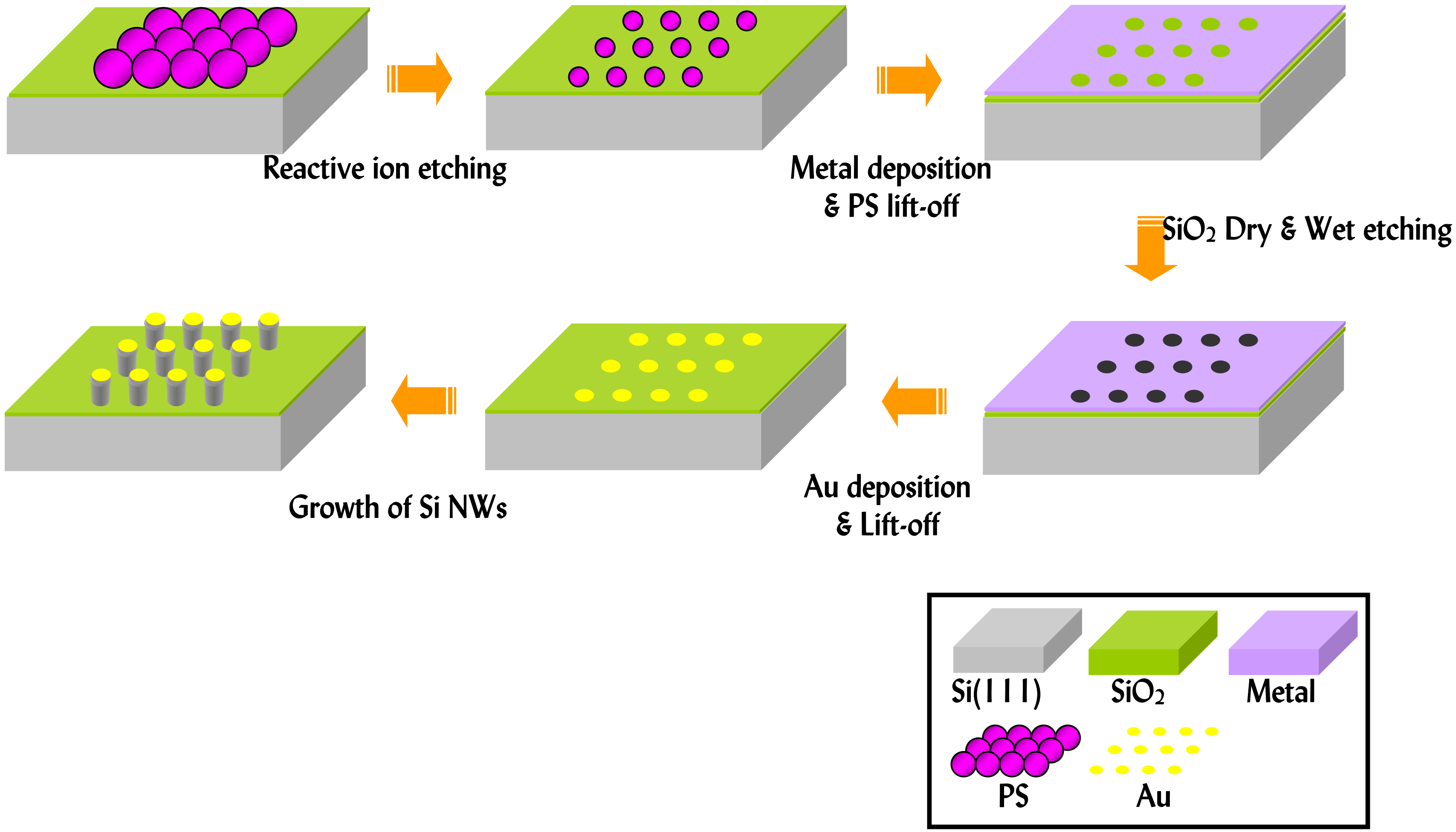
Cheol-Joo Kim et al., *Appl. Phys. Lett.*, In Press (2009)
Kibum Kang et al., *Adv. Mater.* 20 4684 (2008)



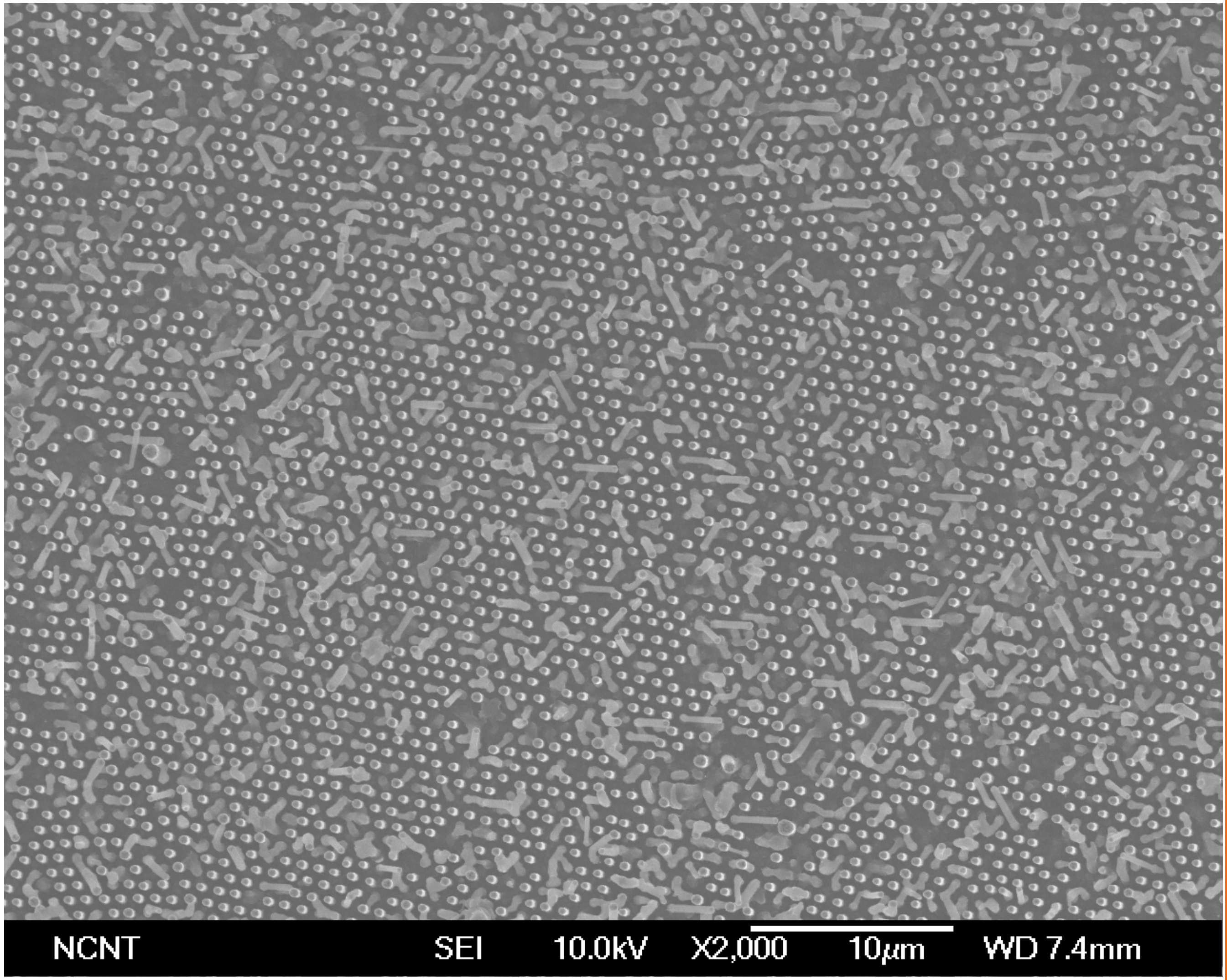



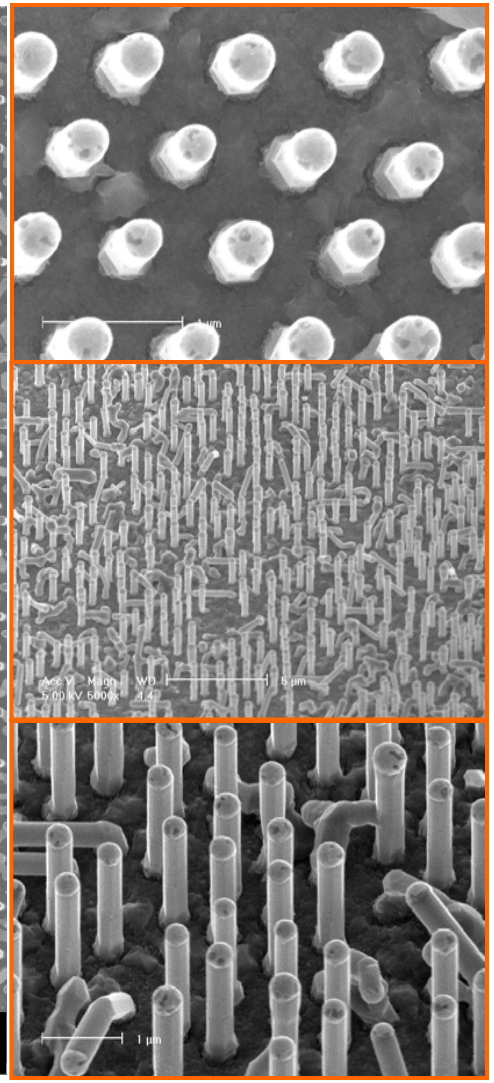
## (I) PS Nanosphere Lithography

Substrate: $SiO_2$(100 nm)/Si(111)-*p*



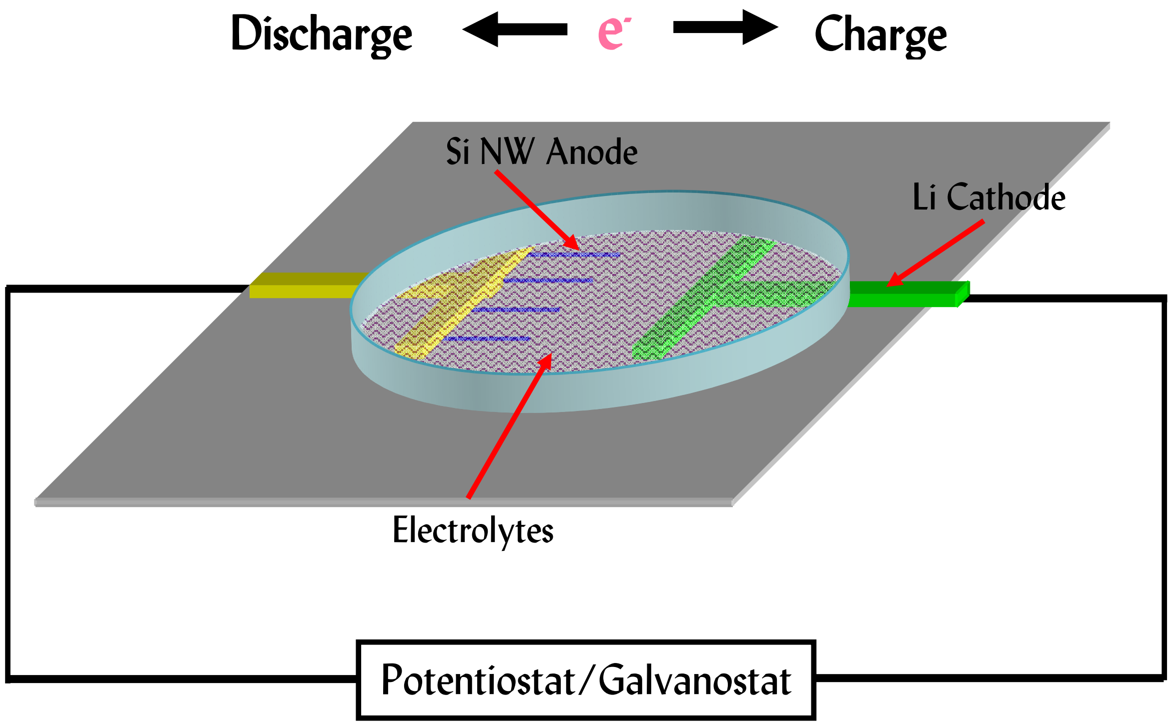
# Si Nanowire Arrays from Au-Catalyst Patterns by Nanosphere Lithography



# Si NW Li-Battery at POSTECH

- World-record Capacity and Efficiency (charging/discharging) up to 4,000 and 99 %!
- Capacity fading is still small and is maintained up to 80 % after 50 cycles !



# Nano Device Materials & Physics Lab

Jee-Eun Yang Hyun-Seung Lee Cheol-Joo Kim Kibum Kang