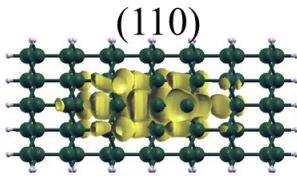


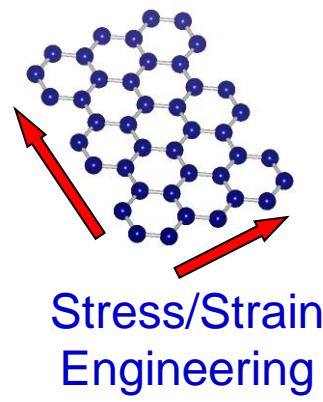
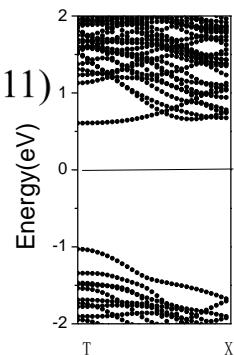
HKIAS Distinguished Lecture Series on Physics

Tuning of Confined Quantum States

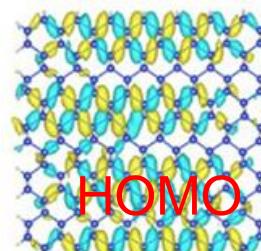
Ruiqin Zhang



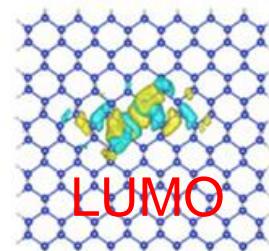
Surface
Engineering



Stress/Strain
Engineering



HOMO

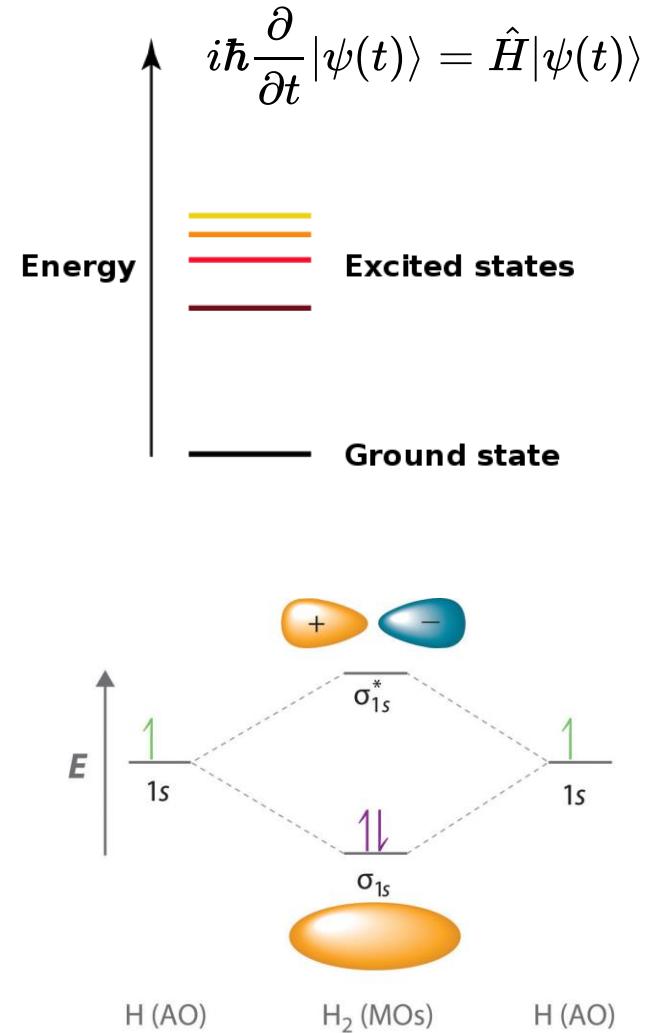
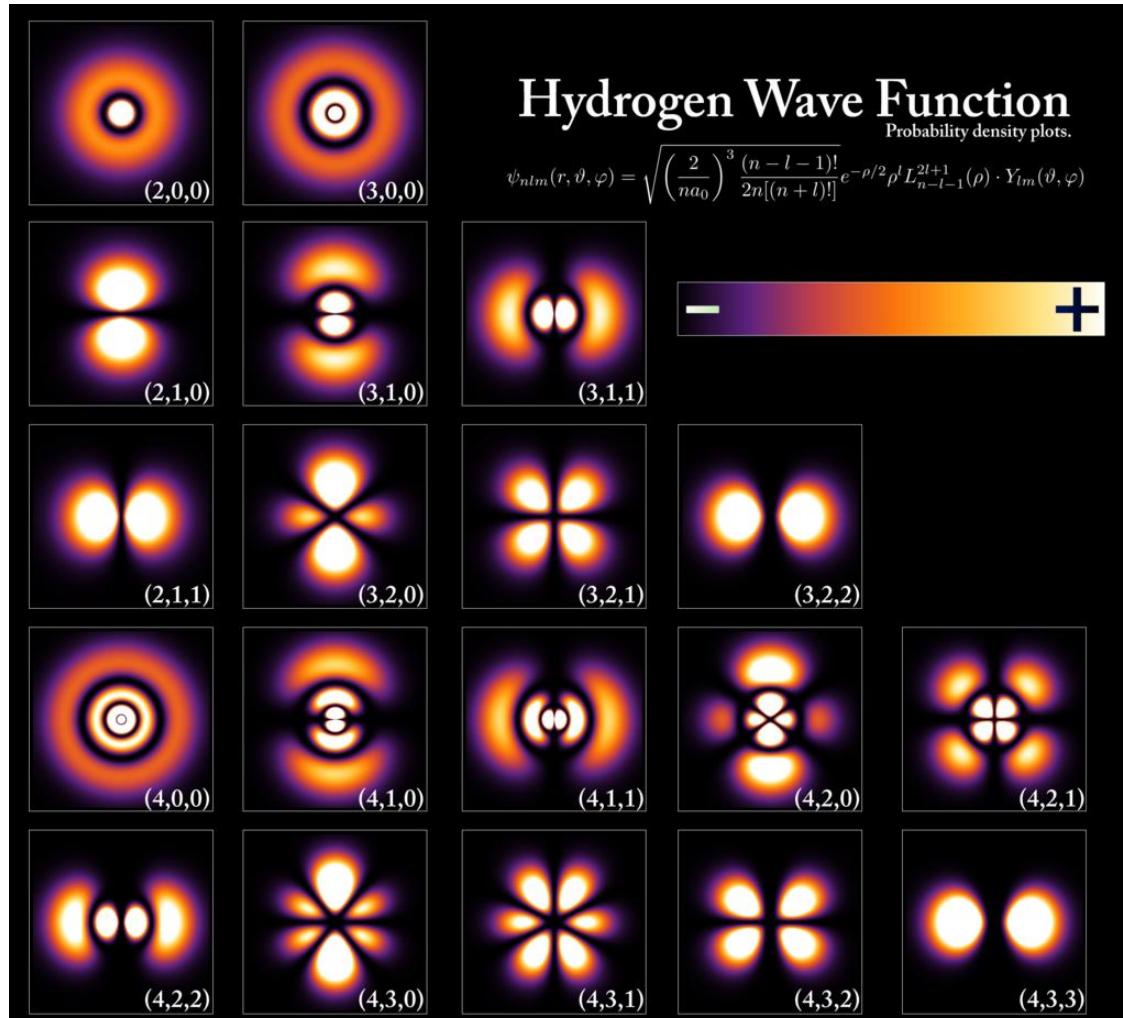


LUMO

Excited State Engineering

Examples of Quantum States

Probability densities for the electron of a hydrogen atom in different quantum states

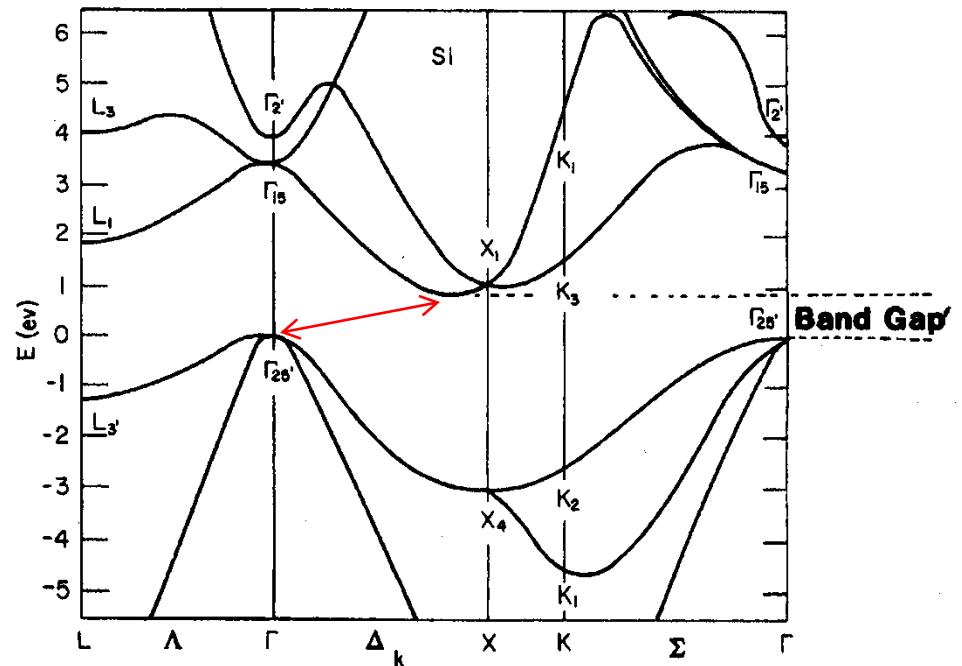


Band structures of silicon



Silicon

Microelectronics vs Photoelectronics



Light Emission from Silicon

S. S. Iyer and Y.-H. Xie

L. T. Canham, *Appl. Phys. Lett.* **57**, 1046 (1990).
 V. Lehman and U. Gösele, *ibid.* **58**, 56 (1991).

SCIENCE • VOL. 260 • 2 APRIL 1993

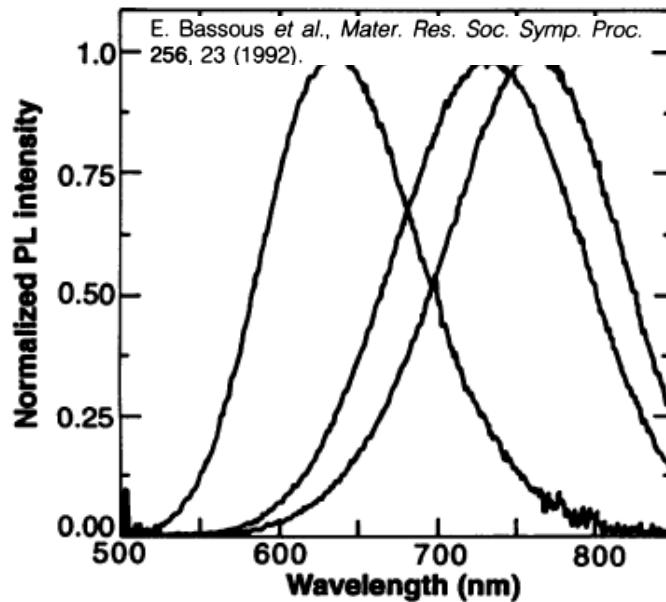
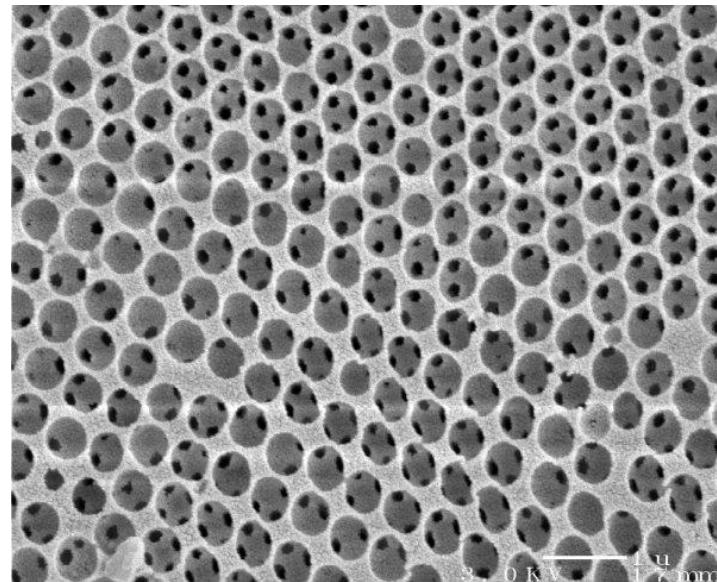


Fig. 9. Typical PL spectra for porous Si etched under different conditions. The blue shift may be a consequence of the greater confinement designers achieve by etching a finer structure (37). The incident power of the laser was 3 mW at 488 nm; experiment done in N₂.

<http://manoharan.deas.harvard.edu/siliconpc>

Porous Silicon

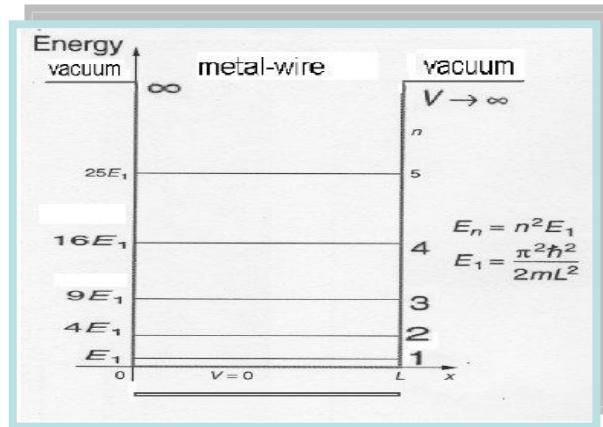
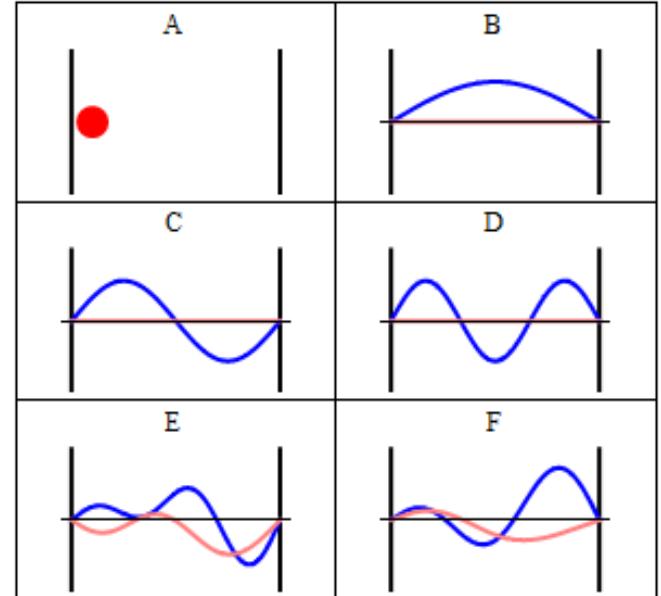
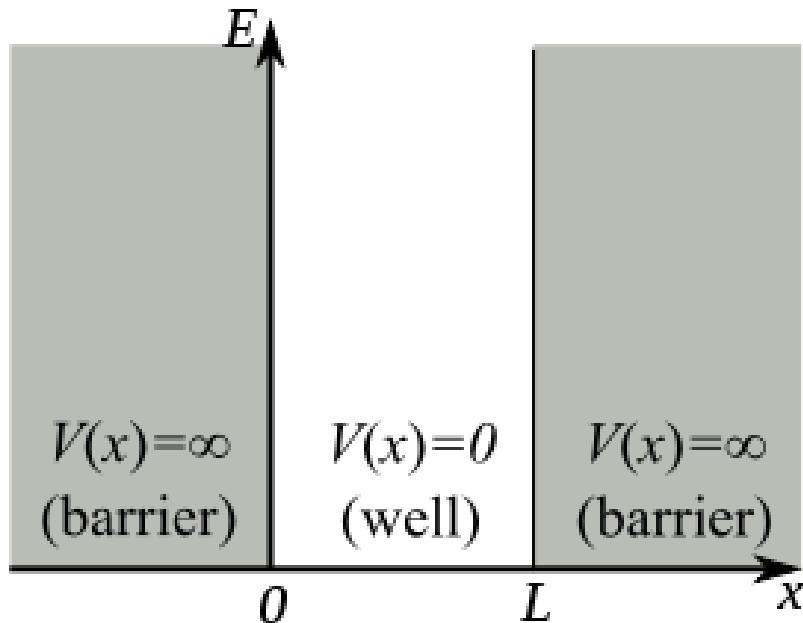


Quantum Confinement Effect

- Surface effect
- Size effect

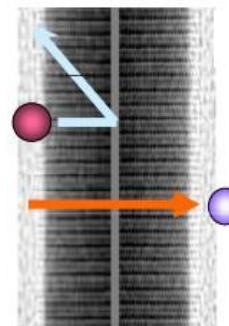
Confined Quantum States

- quantum states confined due to spatial constraint



Mean Free Path
Wavelength

Phonons	Electrons
$\Lambda = 10\text{-}100 \text{ nm}$	$\Lambda = 1\text{-}10 \text{ nm}$
$\lambda = 10\text{-}50 \text{ nm}$	$\lambda = 1 \text{ nm}$

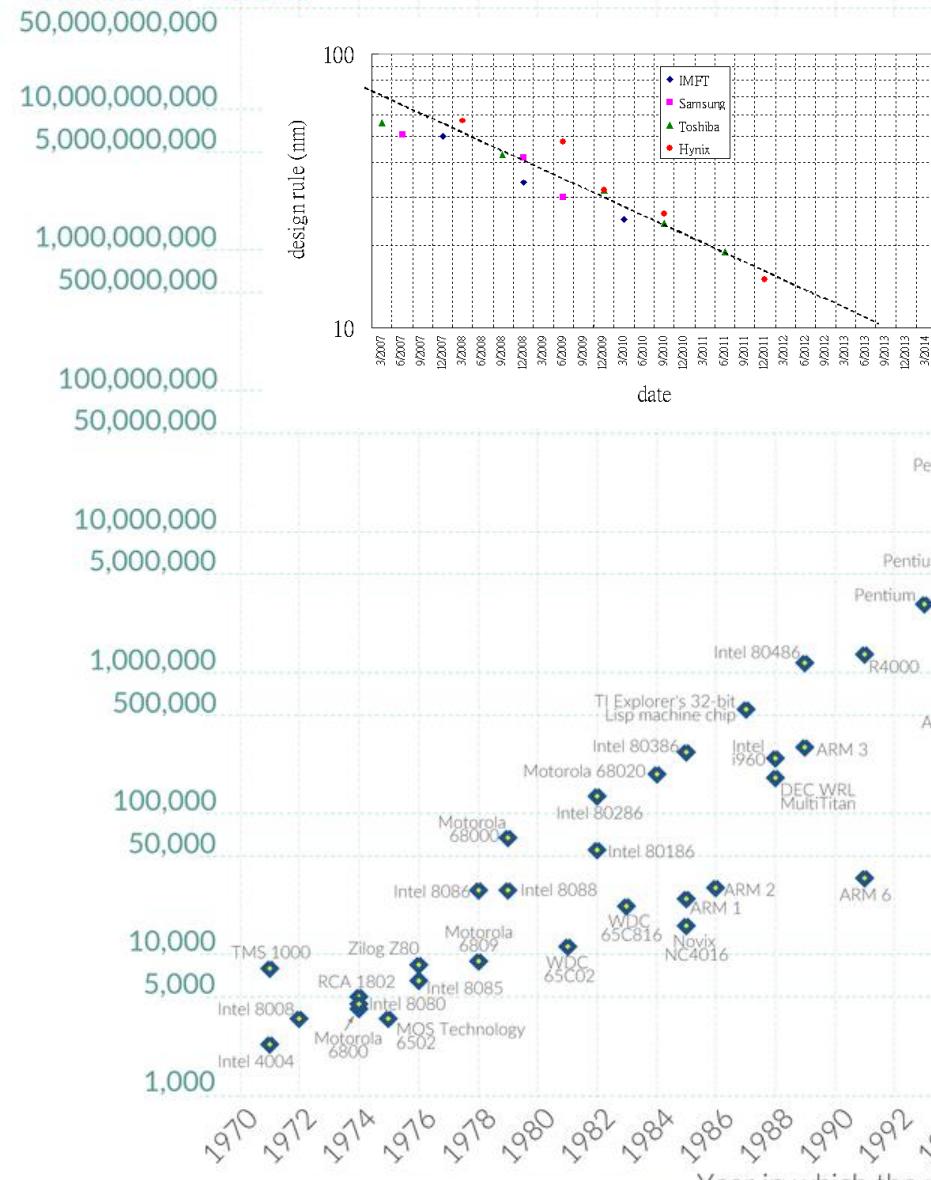


Size matters!

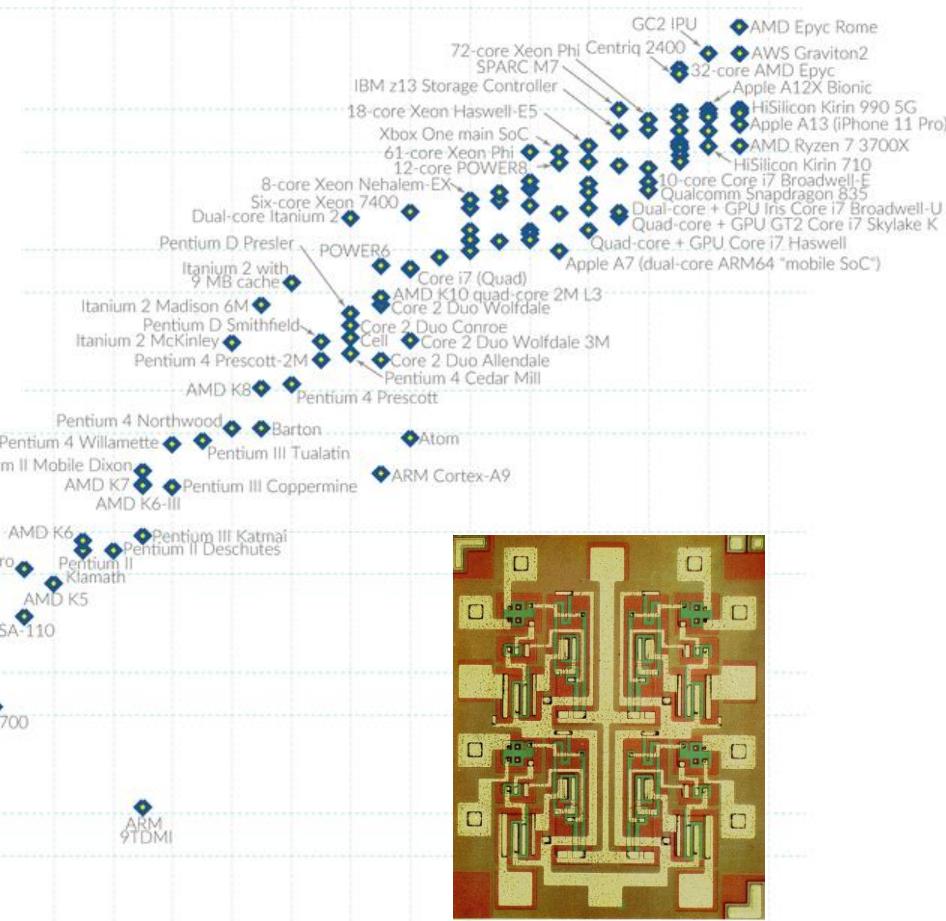
Moore's Law: The number of transistors on microchips doubles every two years

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.

Transistor count



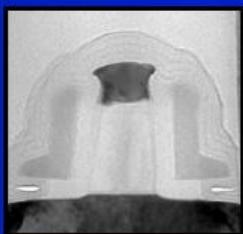
https://en.wikipedia.org/wiki/Moore%27s_law



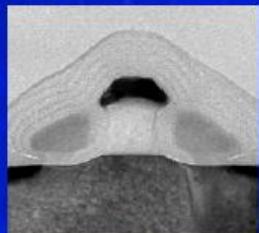
CMOS Device Scaling Demonstration

90nm Node

2003



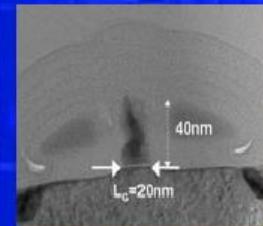
65nm Node
2005



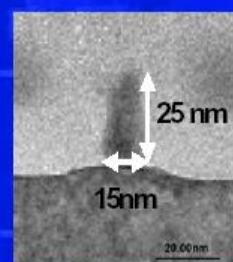
50nm Length
(IEDM2002)

30nm
Prototype
(IEDM2000)

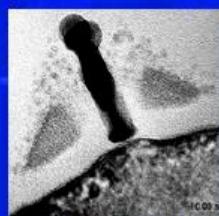
45nm Node
2007



32nm Node
2009

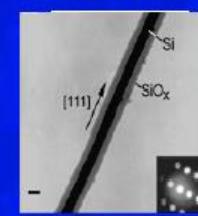


22nm Node
2011

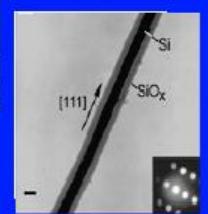


16 nm node
2013

11nm node
2015



8 nm node
2017



15nm Prototype
(IEDM2001)

10nm Prototype
(DRC 2003)

TBD

TBD

Intel's roadmap

Intel research devices scale to 10nm (16nm node)
Channel engineering solutions (Nanowires/Nanotubes)
are being investigated to extend device scaling through
end of next decade

Source: Intel; Morales and Lieber
Science, 279, 208, 1998

Chip thermal management issue: hot spot and thermal removal

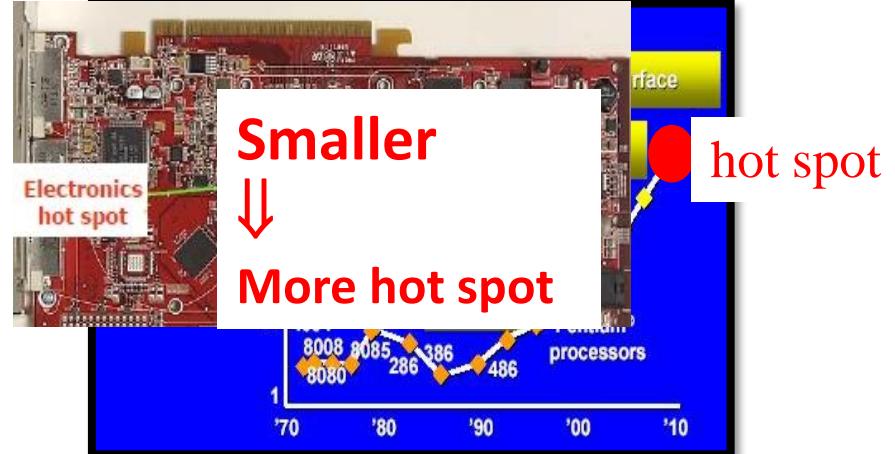
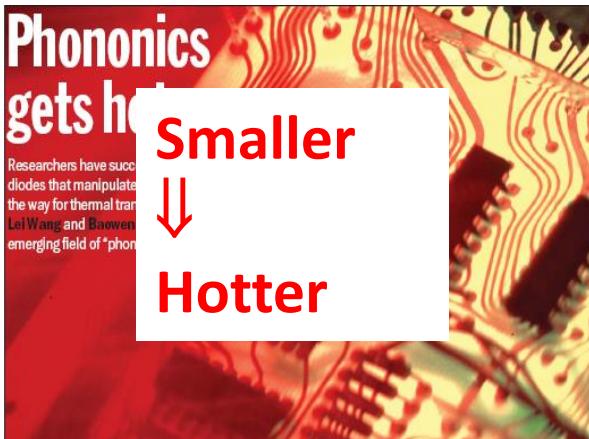
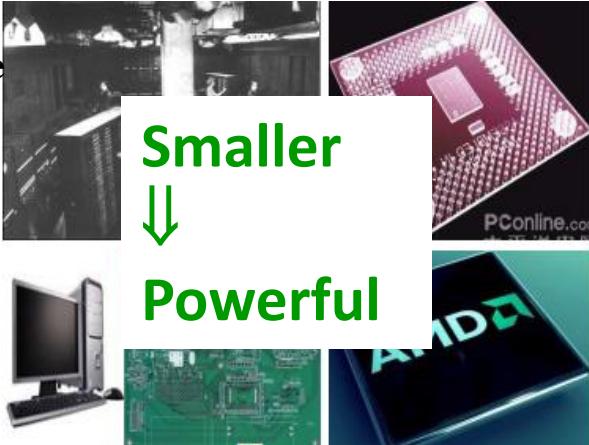
Transistor size

10 mm (1970)

23 nm (2012)

8 nm (2018)

...



Remarks:

- Heat => **bottle neck** for the future development
- **New thermal solution:** high efficiency, energy saving, green

Richard Feynman's Lecture (1959)

"There's Plenty of Room at the Bottom"

An Invitation to Enter a New Field of Physics

"Why cannot we write the entire 24 volumes of the Encyclopedia Britannica on the head of a pin?"

"The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom."

"I don't know how to do this on a small scale in a practical way, but I do know that computing machines are very large; they fill rooms. Why can't we make them very small, make them of little wires, little elements – and by little, I mean little. For instance, the wires should be 10 or 100 atoms in diameter, and the circuits should be a few thousand angstroms across."



Other Concepts:

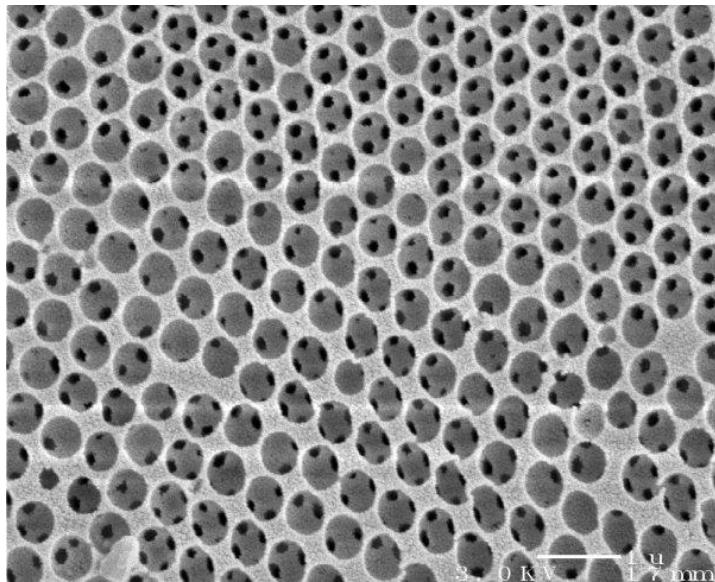
- Rearranging atoms, Micro-machines, Chemical synthesis, Micro-antenna arrays*

Outline

- ✓ Strategy 1: Surface Engineering of Quantum States
- ✓ Strategy 2. Strain/Stress Engineering of Quantum States
- ✓ Strategy 3. Excited State Engineering - *Tuning Exciton Structure in Carbon Nitride and Graphene Quantum Dots for Efficient Solar Energy Harvesting*
- ✓ Summary

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Quantum Confinement Effect

- Surface effect
- Size effect

<http://manoharan.deas.harvard.edu/siliconpc>

L. T. Canham, *Appl. Phys. Lett.* **57**, 1046 (1990).
V. Lehman and U. Gösele, *ibid.* **58**, 56 (1991).

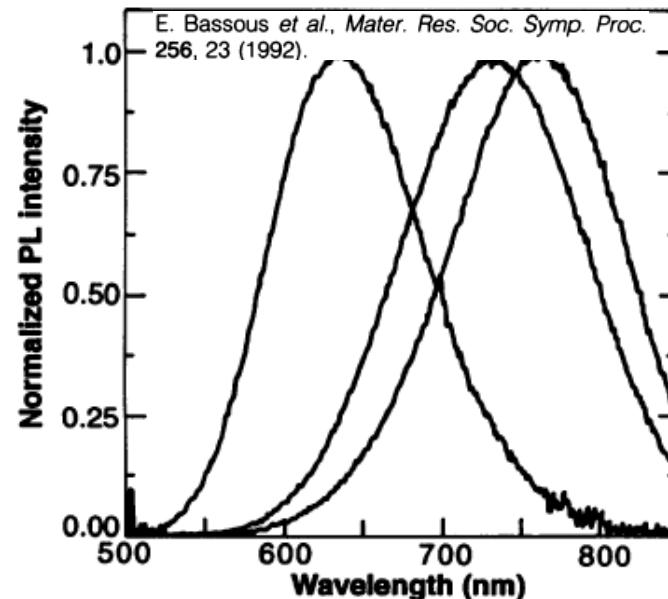
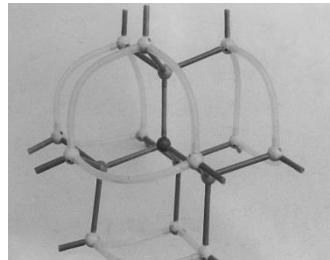


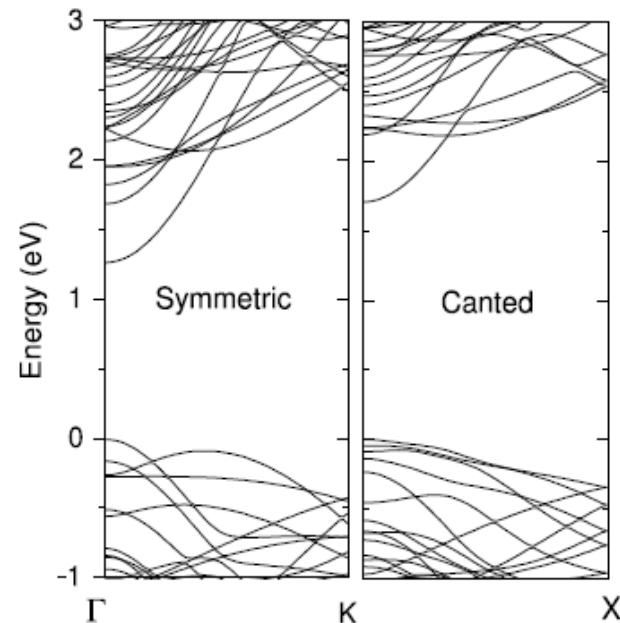
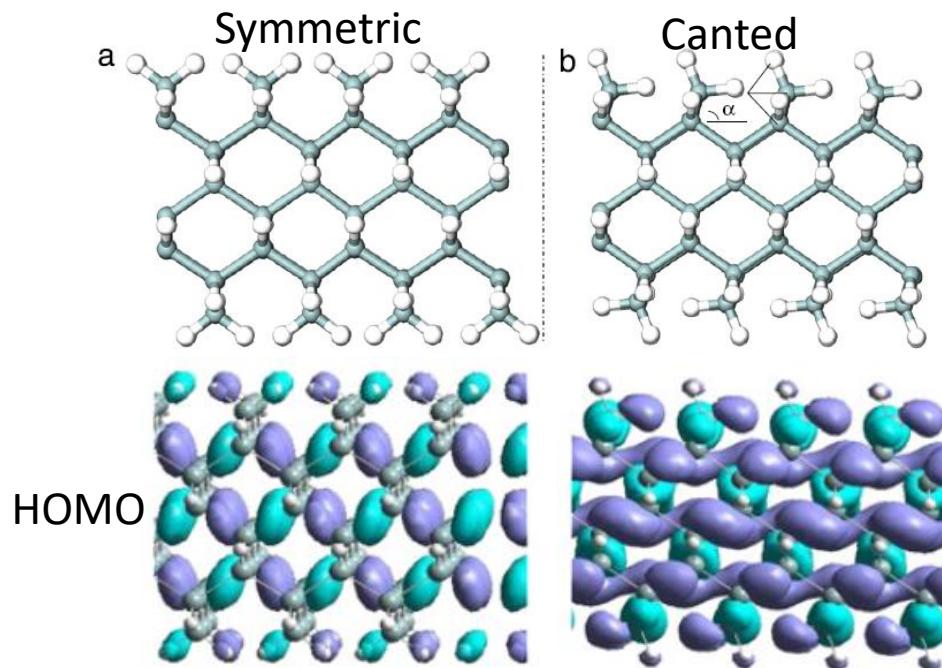
Fig. 9. Typical PL spectra for porous Si etched under different conditions. The blue shift may be a consequence of the greater confinement designers achieve by etching a finer structure (37). The incident power of the laser was 3 mW at 488 nm; experiment done in N₂.



Role of structural saturation and geometry in the luminescence of silicon-based nanostructured materials

R. Q. Zhang,* J. Costa, and E. Bertran

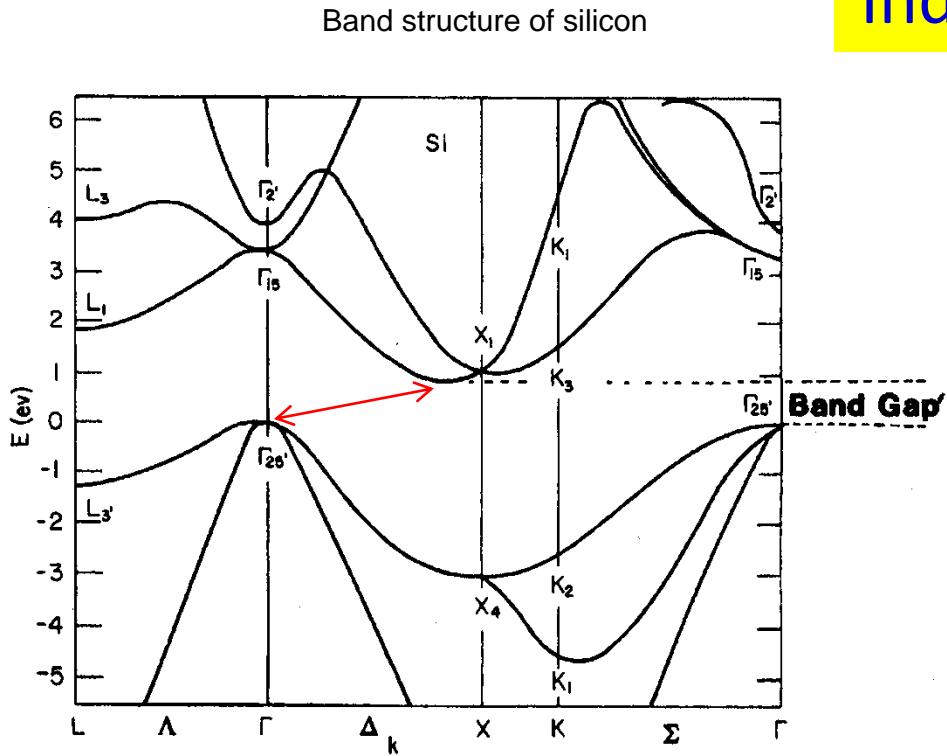
Slight surface structure changes induced significant changes in electronic structures



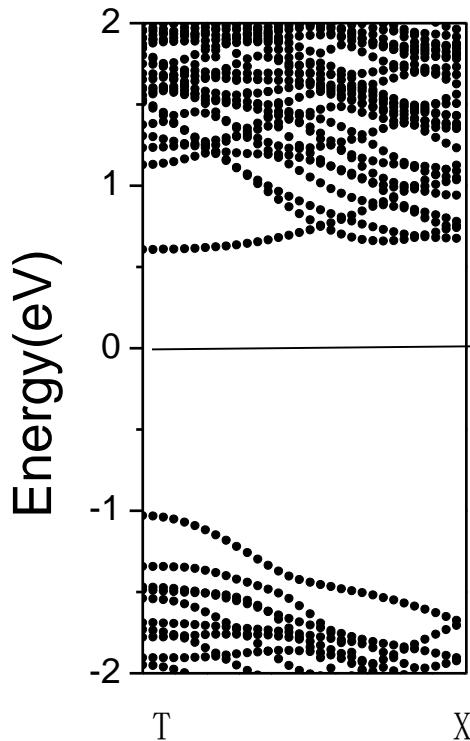
Diameter	Energy difference	Band gap (symmetric)	Band gap (canted)	Band gap difference
1.2 nm (96 atoms)	1.7 eV (0.15 eV/SiH ₂)	1.41 eV	1.79 eV	0.38 eV (~20%)
2.0 nm (248 atoms)	3.0 eV (0.15 eV/SiH ₂)	1.03 eV	1.28 eV	0.25 eV (~20%)

Band structure tuning of SiNWs

Can the sensitive response of electronic structure to surface structure be used to engineer the energy band?

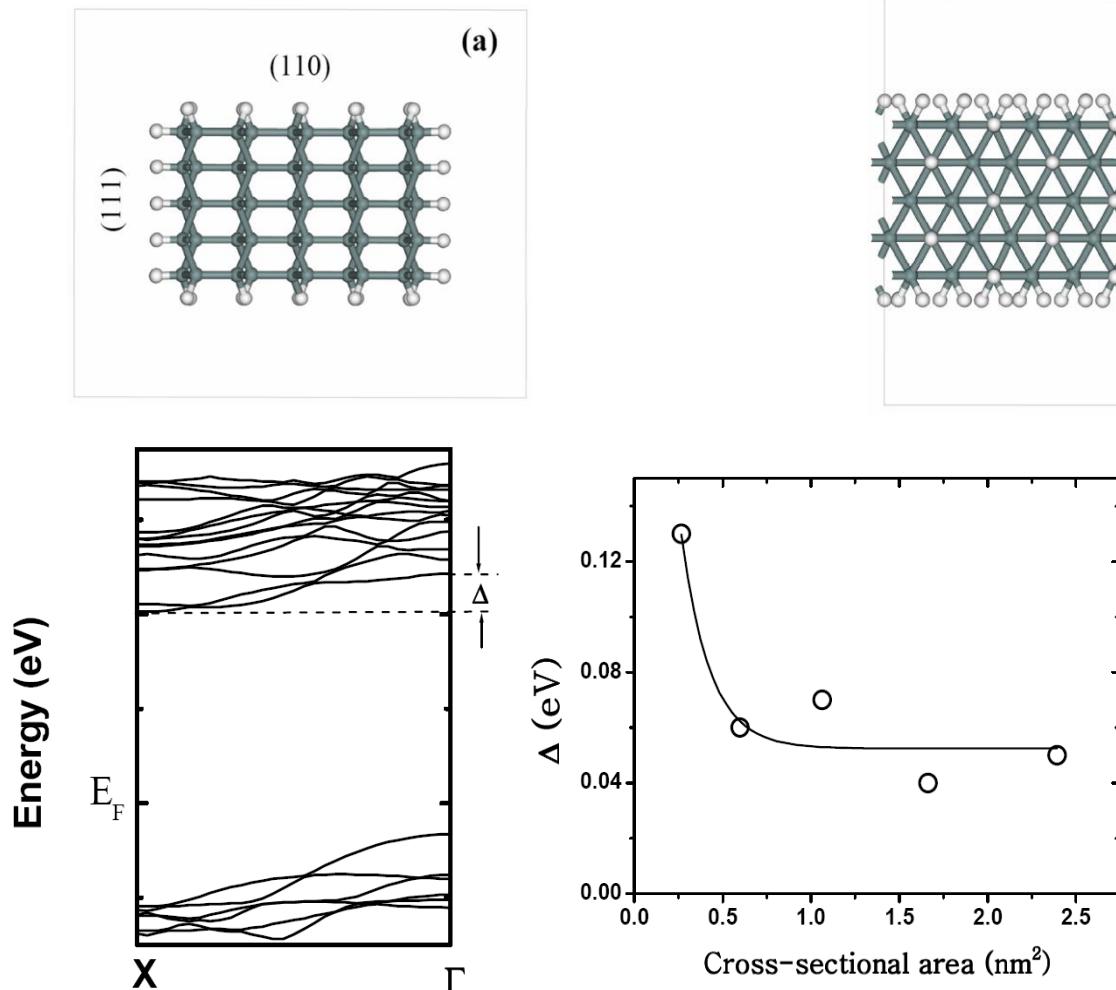


Indirect <==> direct?



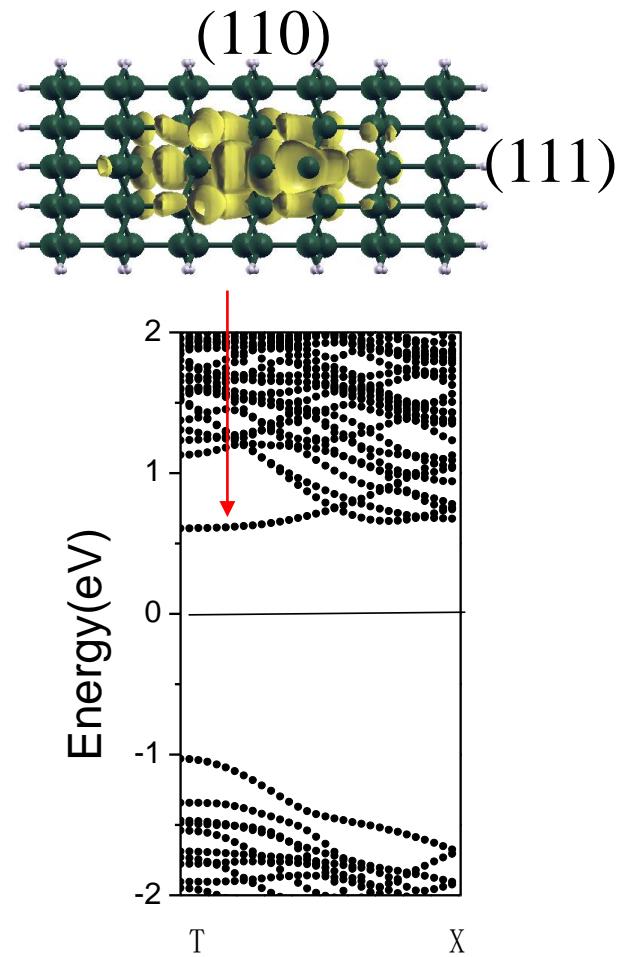
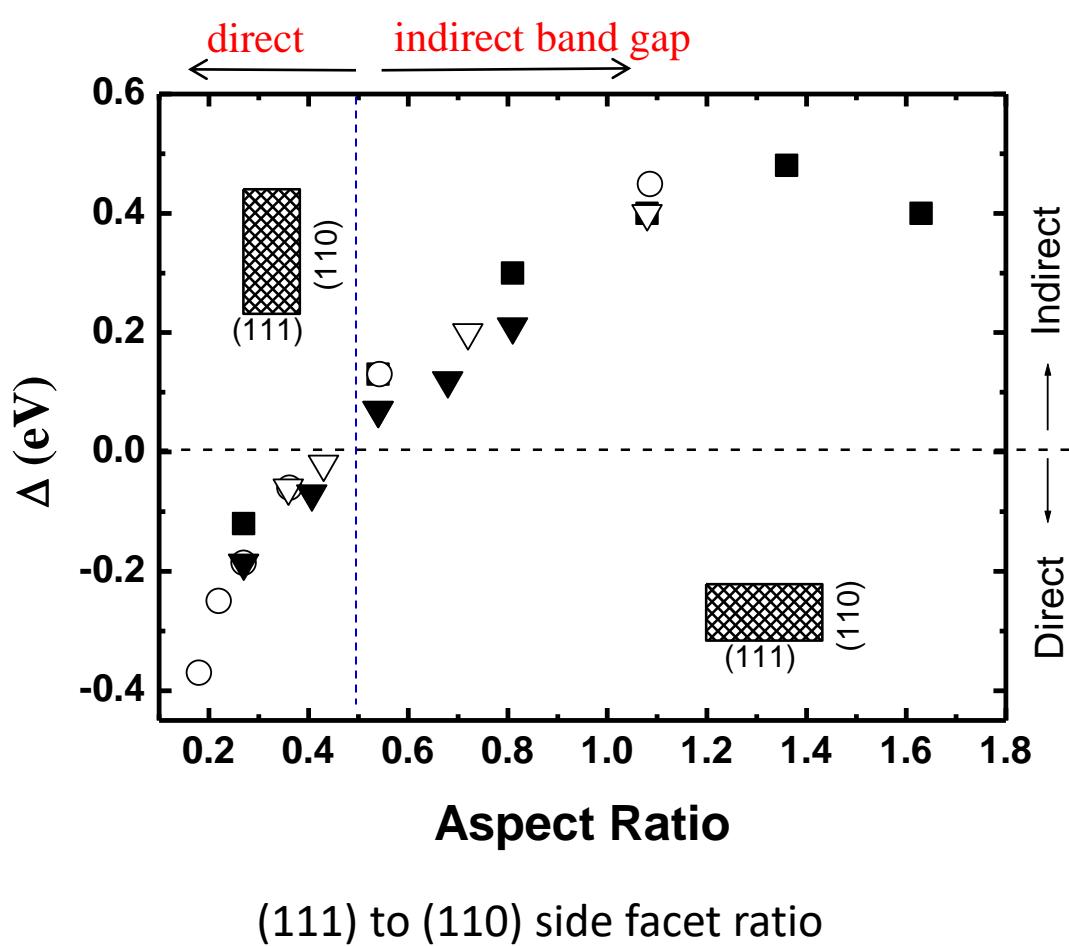
Indirect band structure of <112> SiNWs

Size alone fails to tune the indirect band gap to direct energy gap.



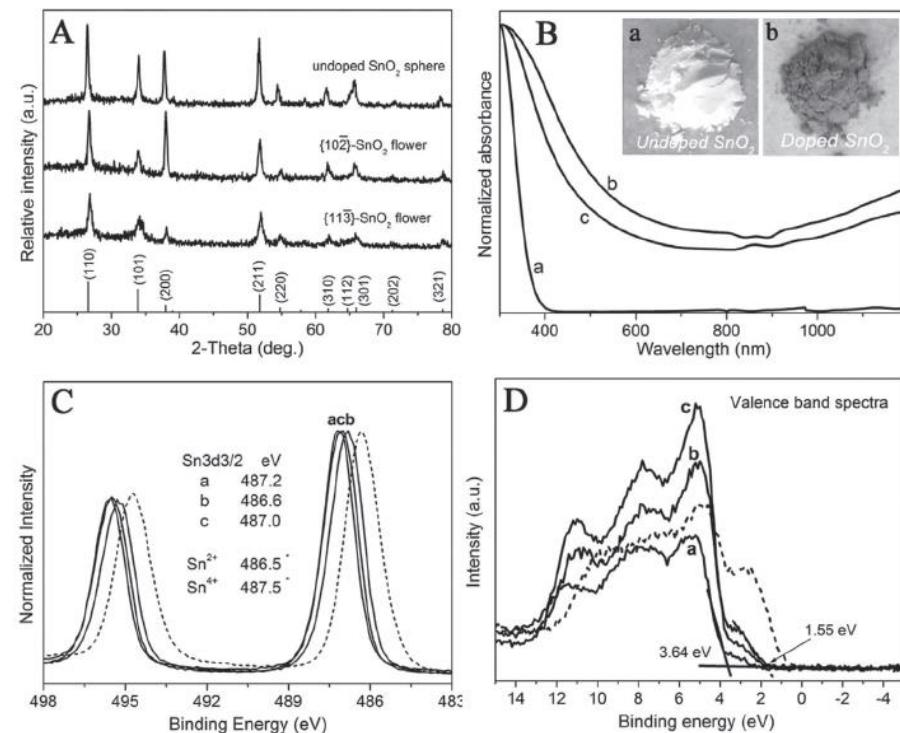
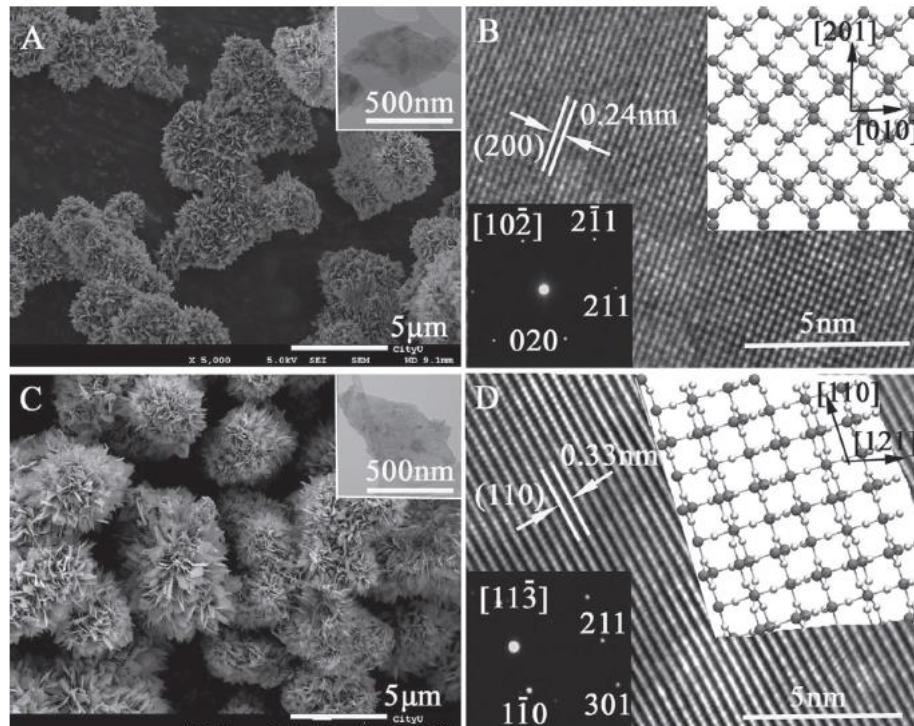
=> quasi-direct
band-gap

Tuning energy band of <112> SiNWs by varying cross-section shape



Hierarchical Sn²⁺ Doped SnO₂ Nanostructures

Tuning the energy band and sensing properties by controlling crystal plane

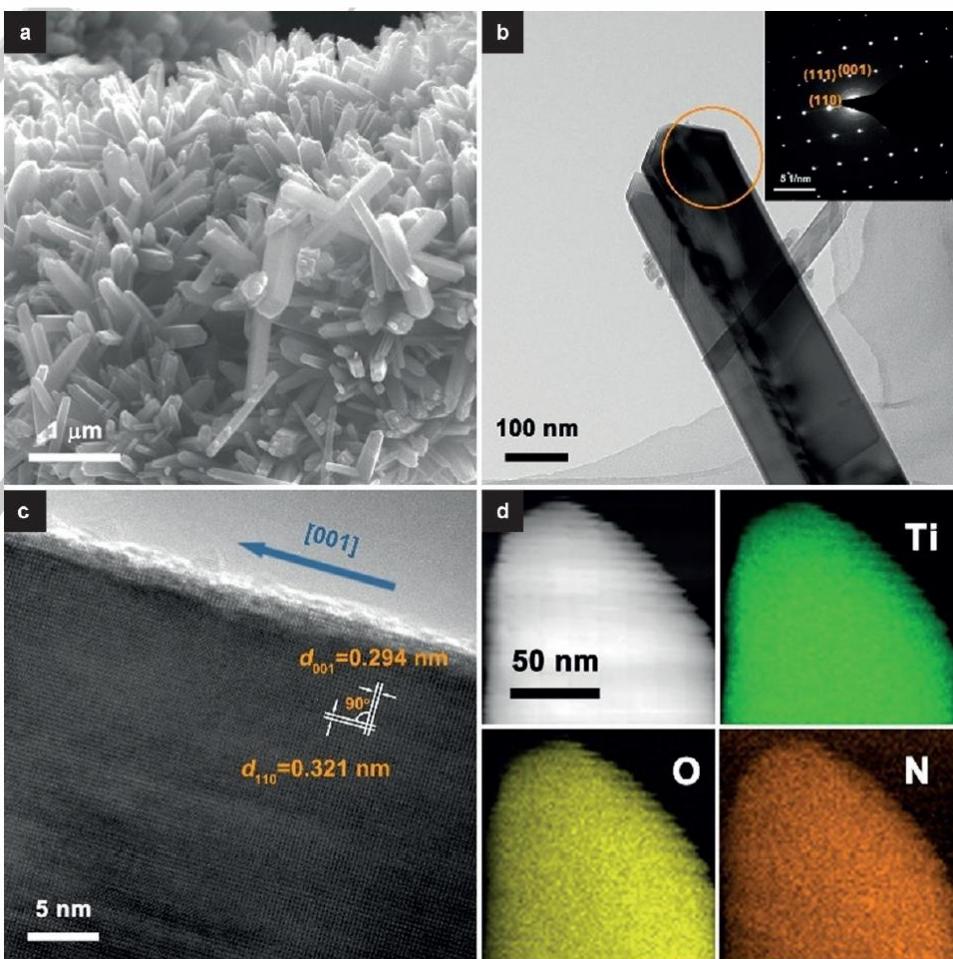
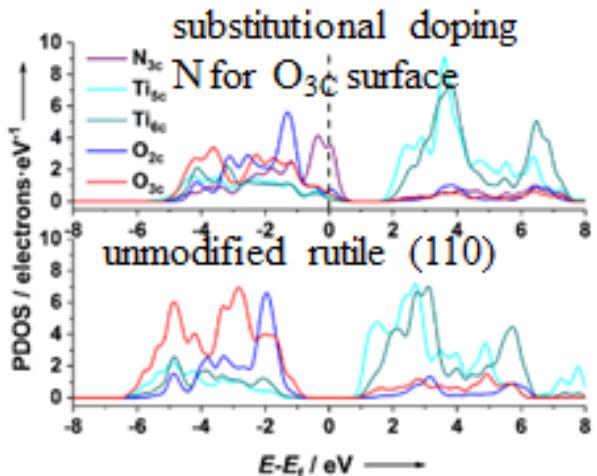
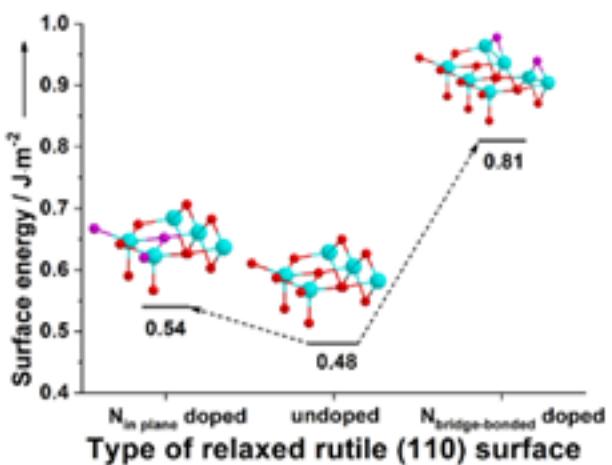


Hierarchical SnO₂ nanoflowers with exposed
A,B) (10̄2) and C,D) (11̄3) facets.



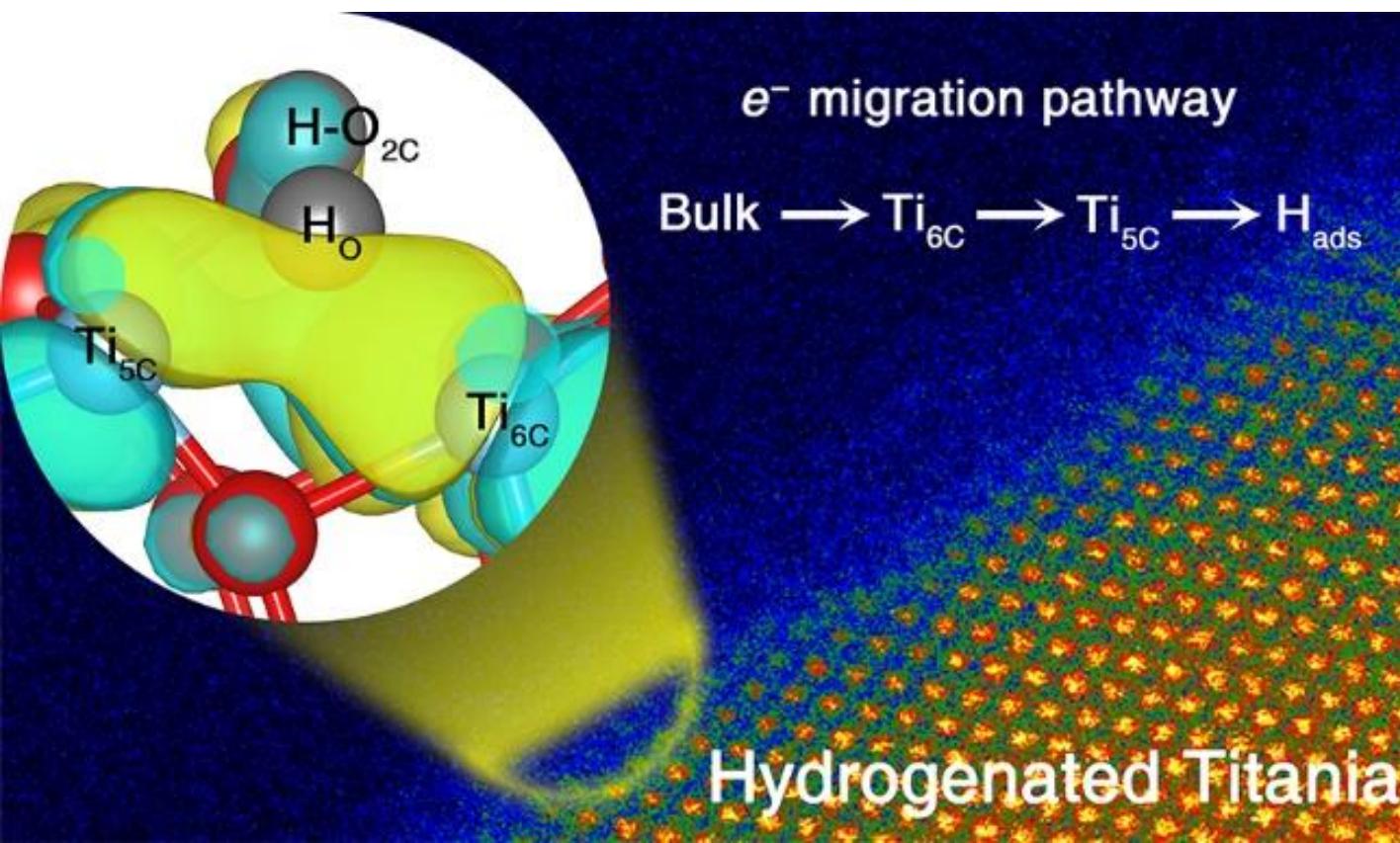
Engineering the Band Gap States of the Rutile TiO_2 (110) Surface by Modulating the Active Heteroatom

Yaoguang Yu, Xu Yang, Yanling Zhao,* Xiangbin Zhang, Liang An, Miaoyan Huang, Gang Chen, and Ruiqin Zhang*



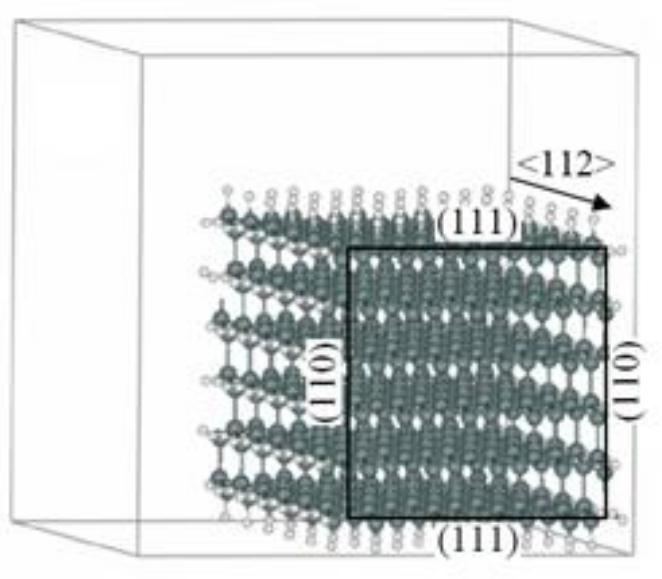
Hydrogen-Location-Sensitive Modulation of the Redox Reactivity for Oxygen-Deficient TiO_2

Yao Guo,^{†,‡} Shunwei Chen,[†] Yaoguang Yu,^{*,†,§} Haoran Tian,[†] Yanling Zhao,^{†,‡,§} Ji-Chang Ren,^{||} Chao Huang,[†] Haidong Bian,[#] Miaoyan Huang,[†] Liang An,^{†,⊥} Yangyang Li,^{#,§} and Ruiqin Zhang^{*,†,§}



The origin of the outstanding redox reactivity for hydrogenated TiO_2 has been unveiled to be a synergy of surface H heteroatoms located at different surface sites.

Surface passivation inducing charge transfer and thus doping



$$Q = 8q / (a^2 D)$$

q : charge on a H = -0.06 |e|

a : lattice constant 5.43 Å

D : the diameter = 100 nm

H(SiH)	Si(SiH)
-0.06	0.05

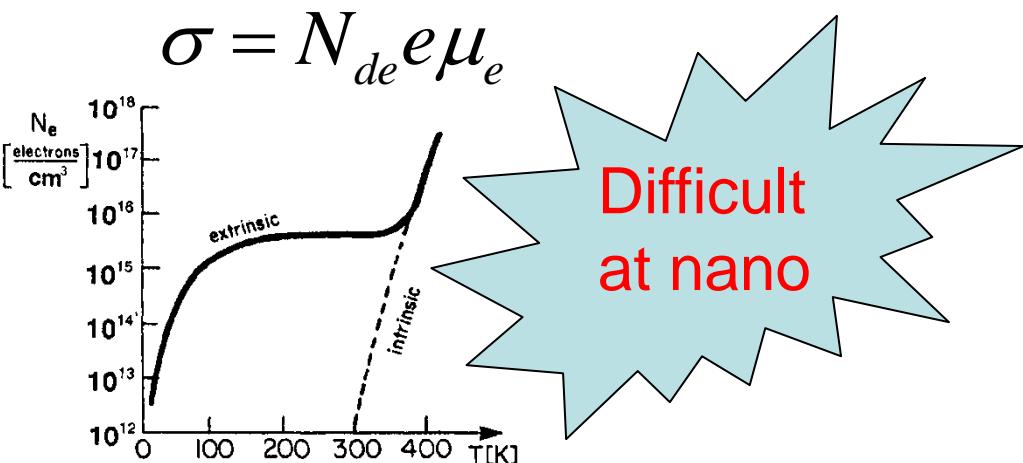
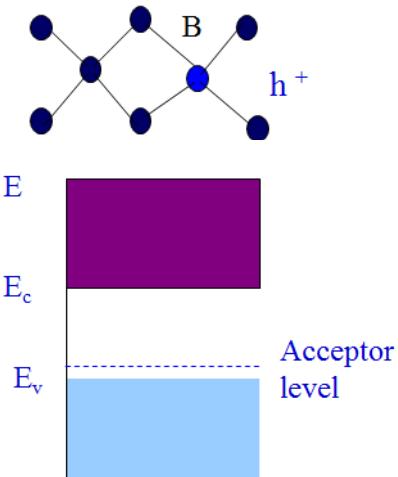
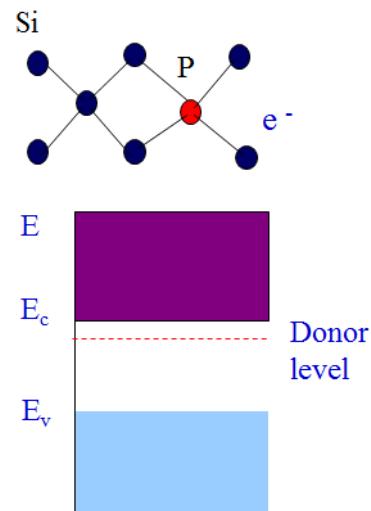
M.X. He, R.Q. Zhang, et al.,
J. Theor. Comput. Chem., 8, 299–316 (2009).

Hole concentration due to surface doping: 10^{19} cm^{-3}

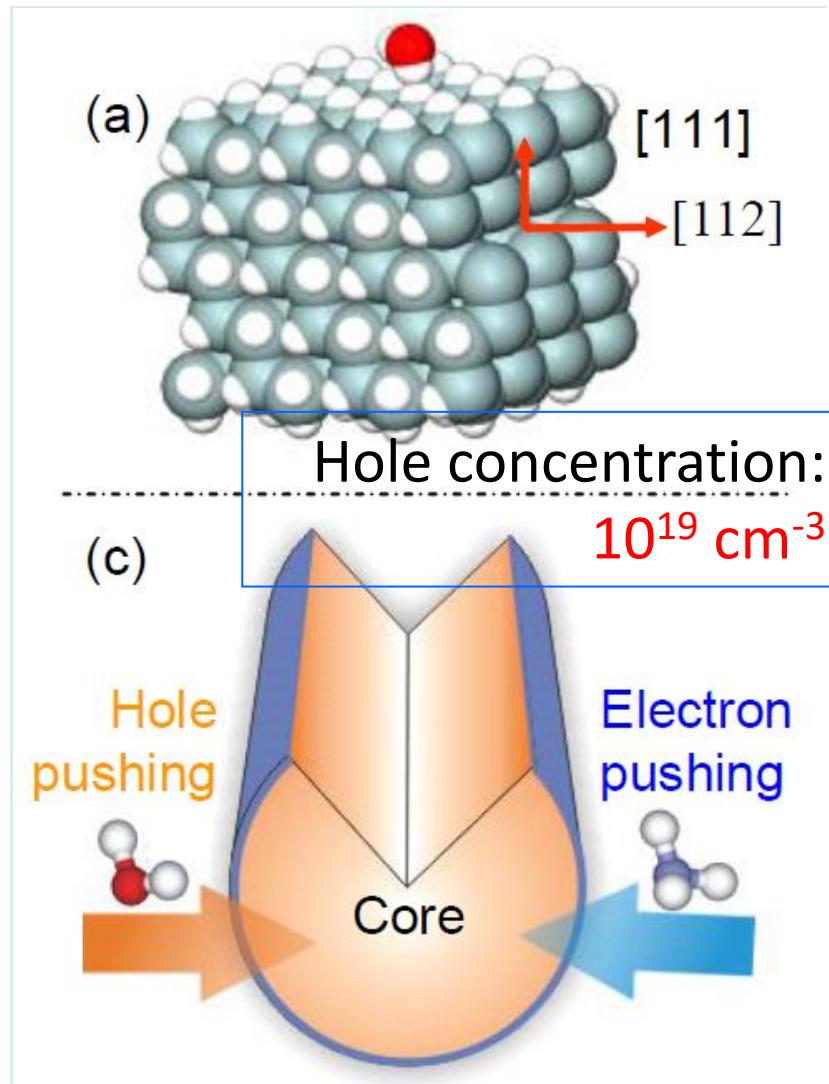
C.S. Guo, R.Q. Zhang*, et al.,
Angew. Chem. Int. Ed, 48/52,
9896(2009).

Achieving effective doping by tuning surface composition

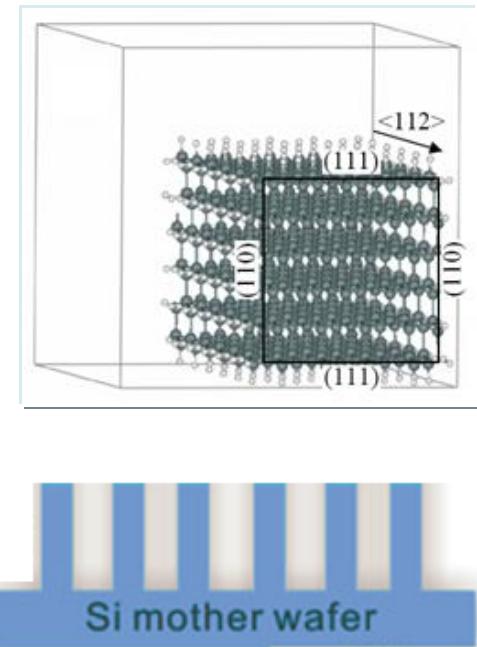
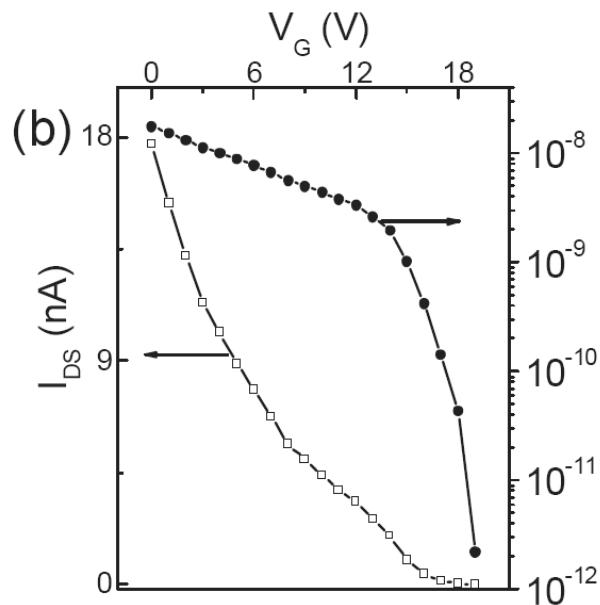
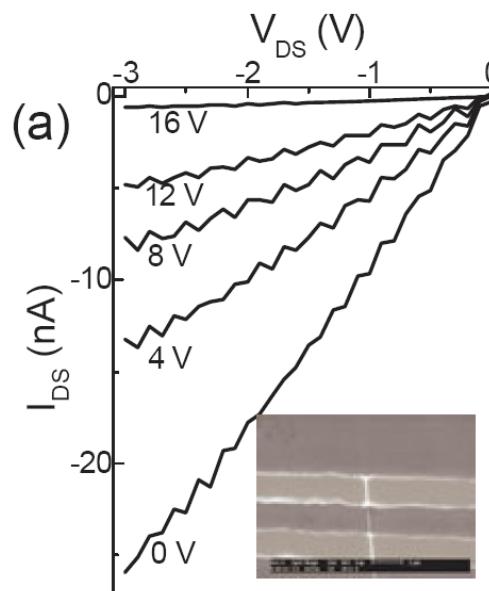
Conventional volume doping



Surface doping



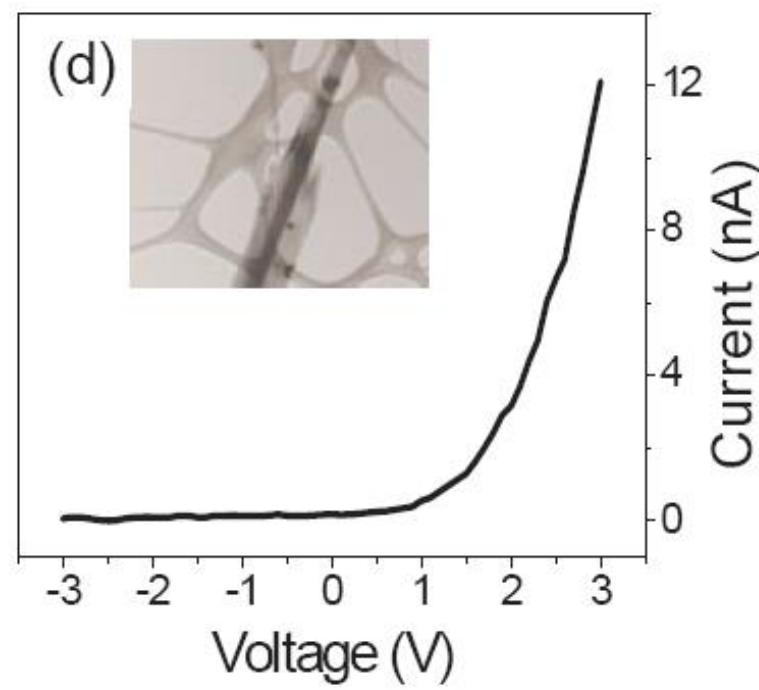
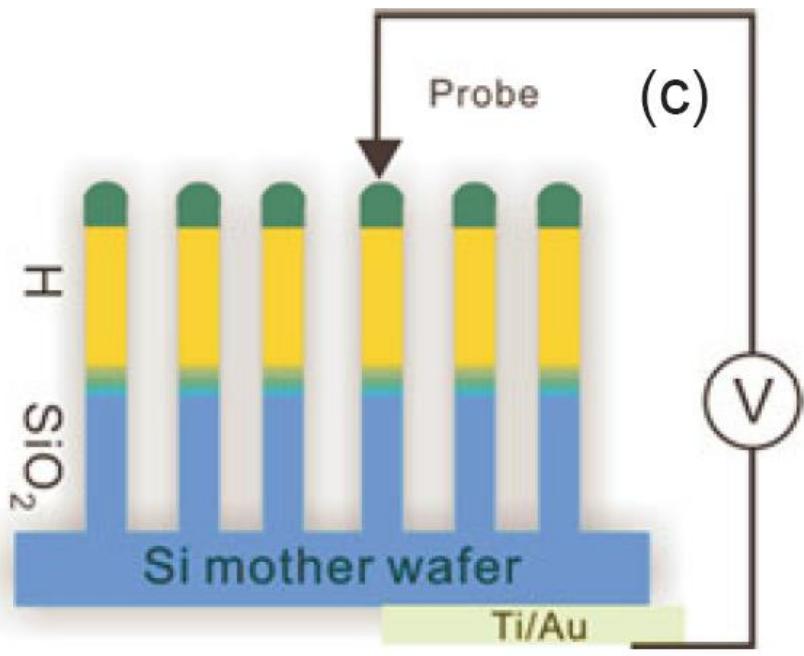
Experimental verification of surface passivation doping



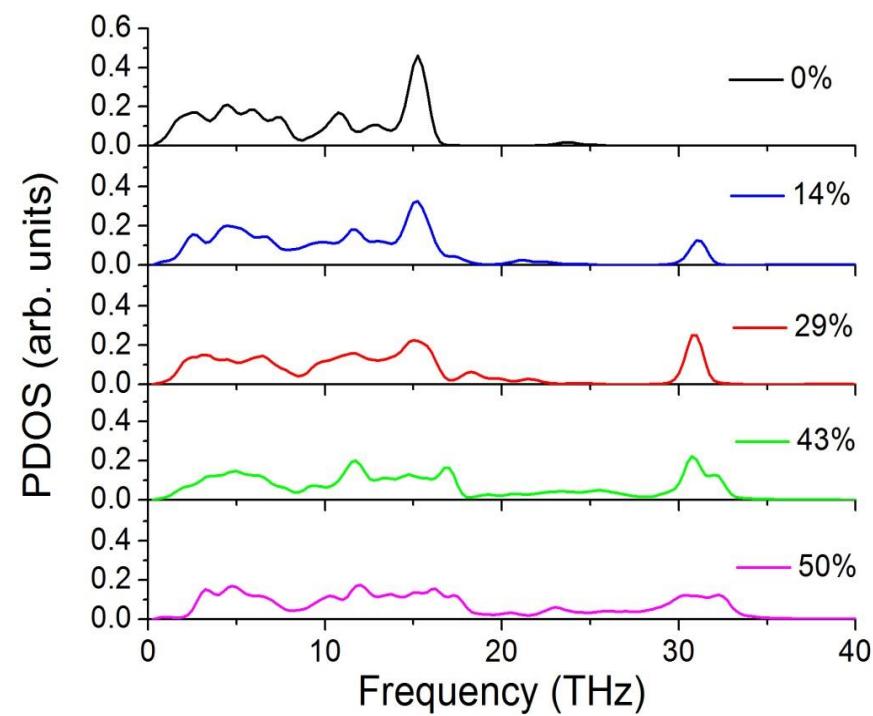
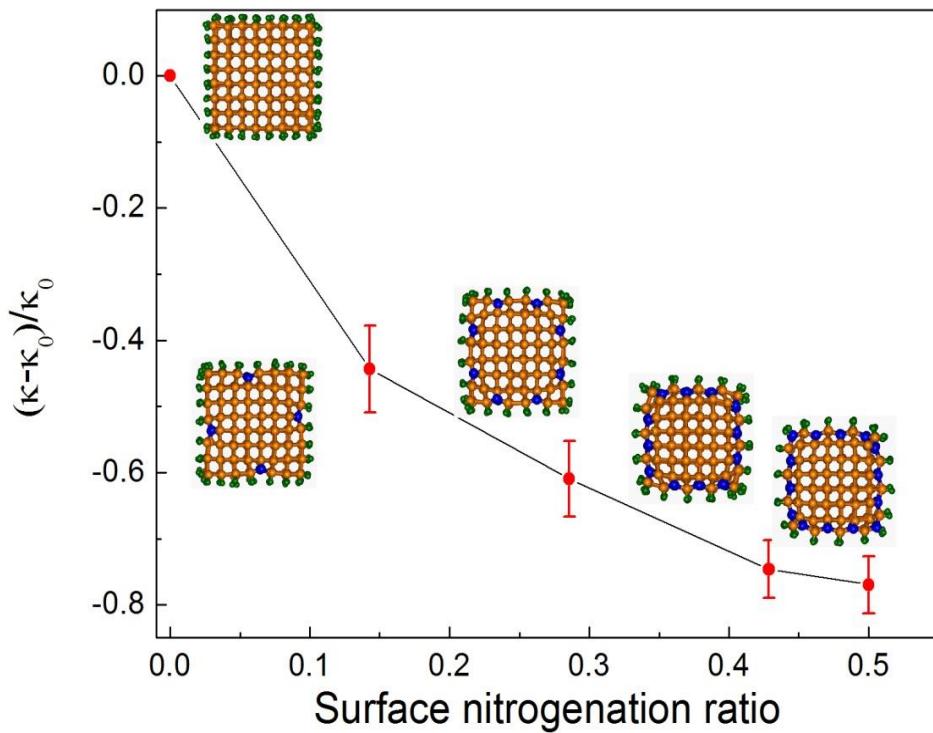
	Original Si wafer	H-SiNWs in vacuum	
	p	μ	p
Sample 1	1×10^9 (intrinsic)	0.235	9.6×10^{17}
Sample 2	3.3×10^6 (weak n)	1.83	4.1×10^{17}

A p-n junction array by surface passivation doping

p-n diode array



Thermal conductivity reduction due to surface nitridation



- Surface nitrogenation \Rightarrow surface lattice deformations
- Remarkable phonon-defects scattering on the surface
 - \Rightarrow low frequency PDOS \downarrow
 - \Rightarrow reduction of thermal conductivity

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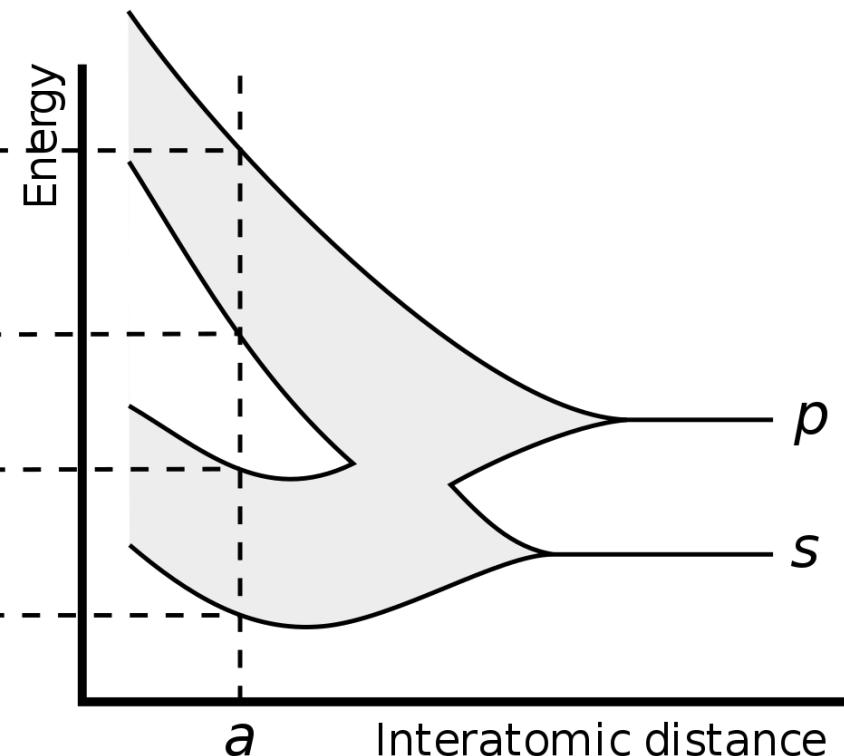
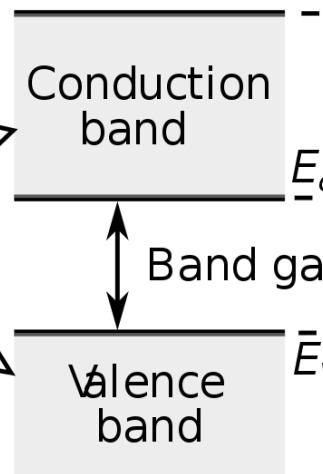
energy level split
orbital hybridization

atomic distance decrease

stress increase

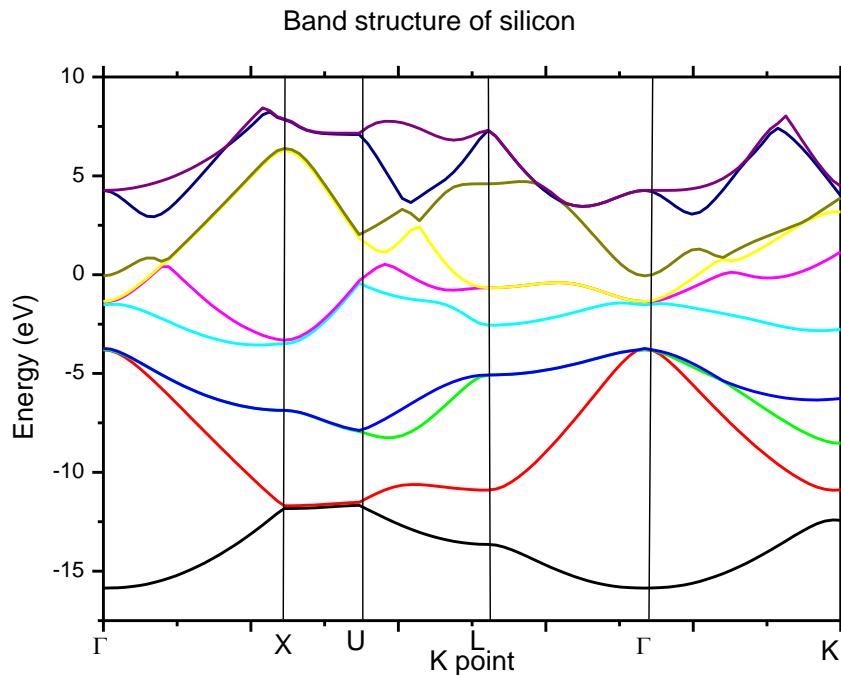
$\sim 10^{-22}$ eV

"Bands" are composed of closely spaced orbitals



https://en.wikipedia.org/wiki/Electronic_band_structure

Energy band engineering of silicon crystal



Tsay & Bendow, PRB 16, 2663(1977)

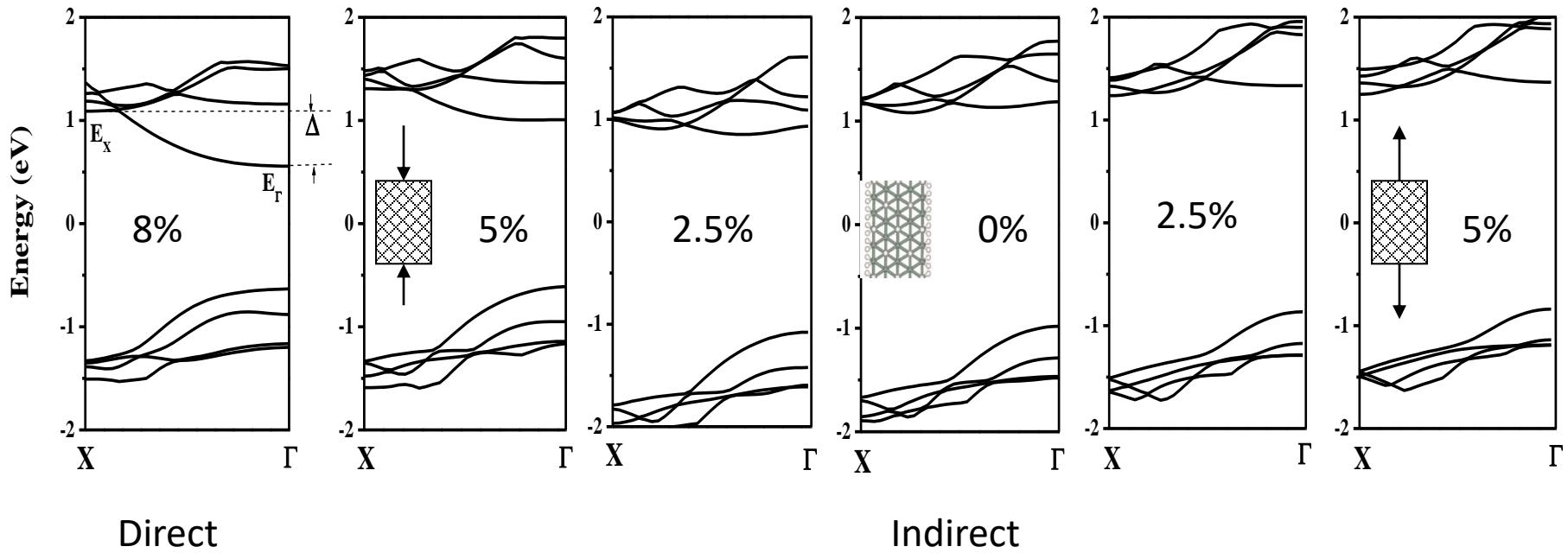
Bulk Si crystal:

Applying 0.02 strain in
 $<001>$ or $<111>$ induced
 conduction band
 minimum splitting at Γ
 point

Is it more effective for low dimensional systems?

Stress-induced band gap tuning in <112> silicon nanowires

A.J. Lu, R.Q. Zhang*, et al., **Applied Physics Letters**, 91, 263107 (2007)



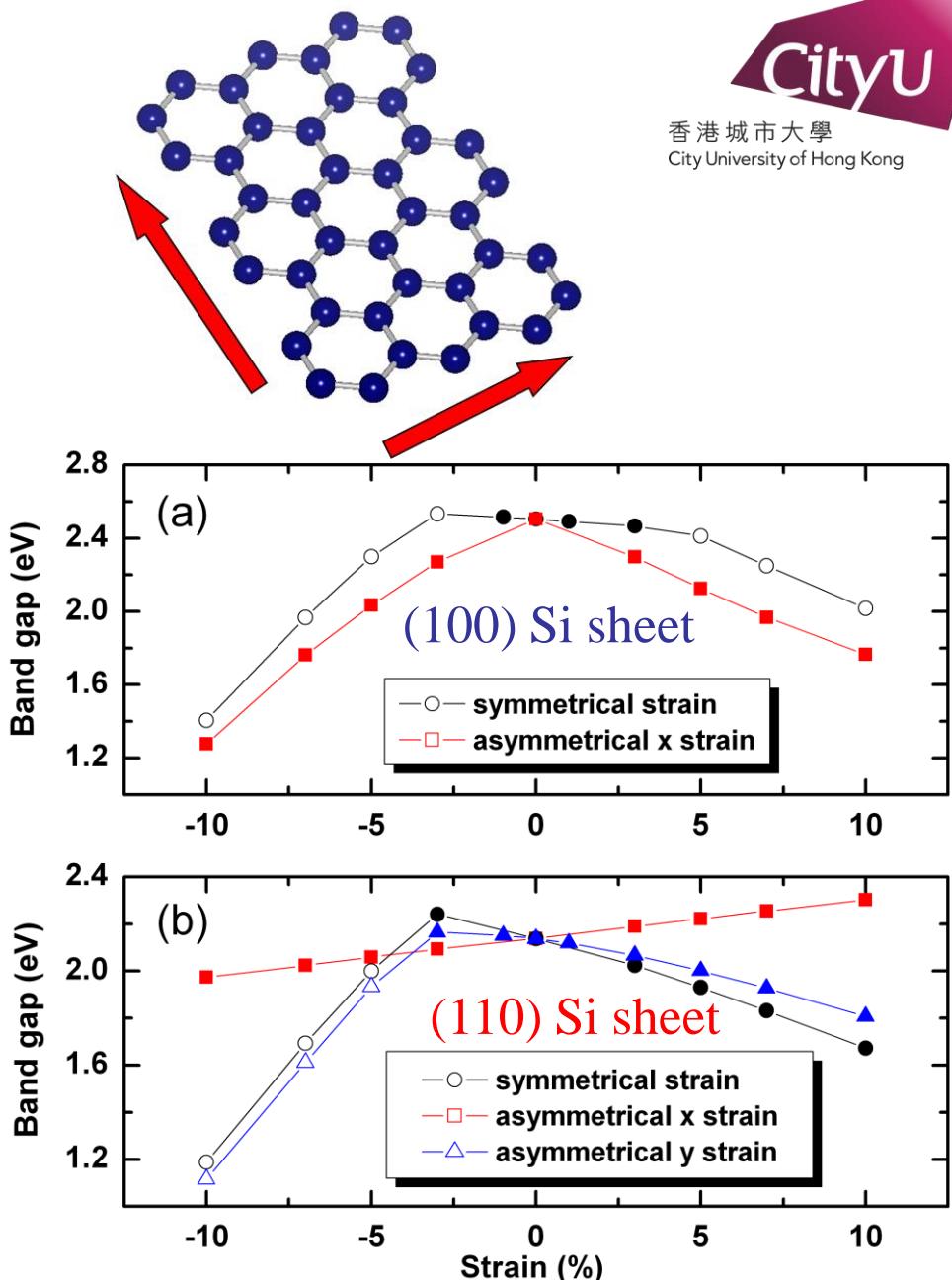
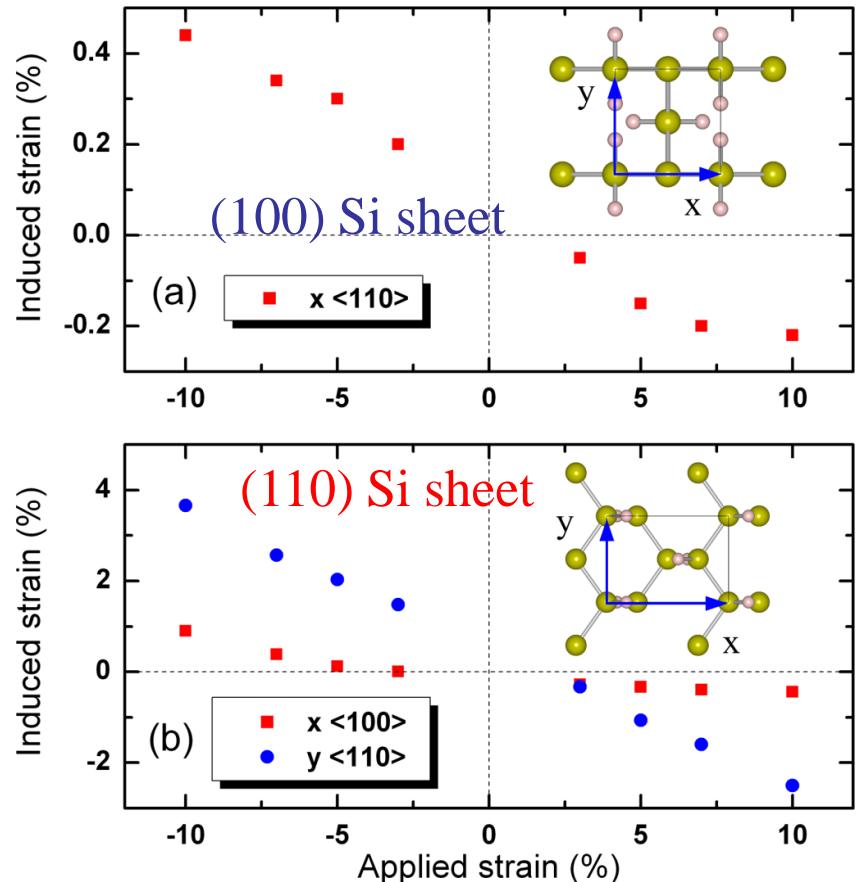
Electronic and elastic properties of <110> and <111> Si NWs

P. W. Leu, A. Svizhenko, and K. Cho, **Phys. Rev. B** 77, 235305 (2008). Stanford

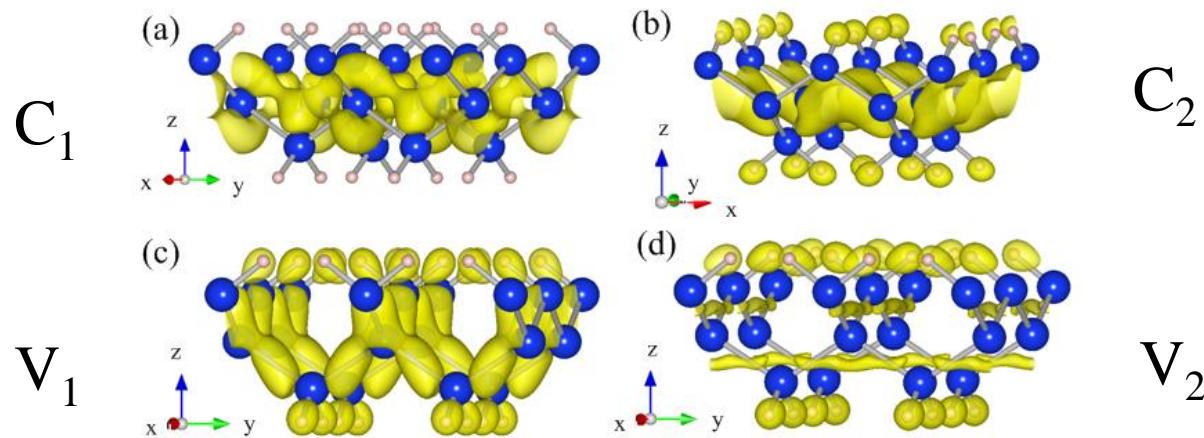
Electronic properties tuning of <100>,<110> and <111> Si NWs

K. H. Hong, J. Kim, S. H. Lee, and J. K. Shin, **Nano Lett.** 8, 1335 (2008). Korea

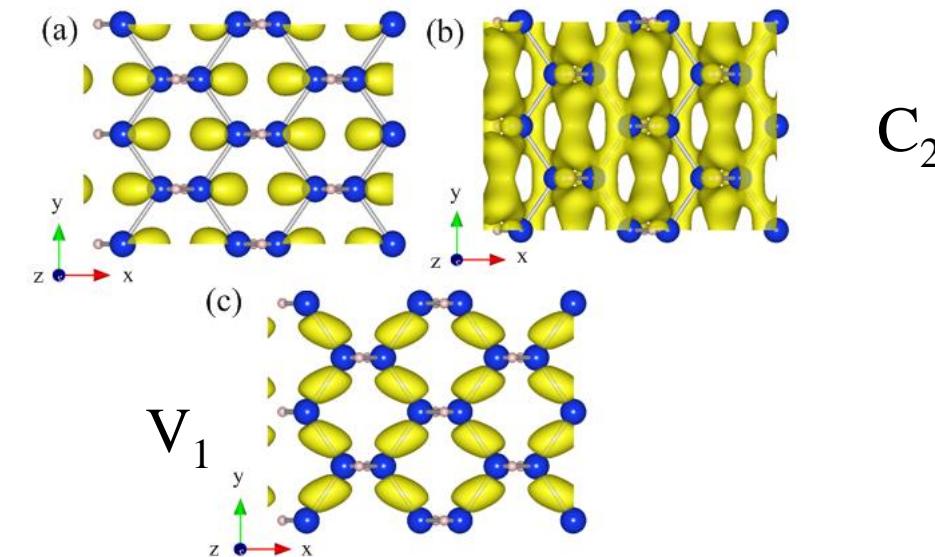
2D: Induced strain vs applied strain



(100) Si sheet



(110) Si sheet





Articles

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Strain engineering of graphene's electronic structure

[VM Pereira, AHC Neto - Physical review letters, 2009 - APS](#)

We explore the influence of local **strain** on the electronic structure of graphene. We show that **strain** can be easily tailored to generate electron beam collimation, 1D channels, surface states, and confinement. These can be seen as basic elements for all-graphene ...

Cited by 1007 Related articles All 8 versions

Strain engineering of graphene: a review

[C Si, Z Sun, F Liu - Nanoscale, 2016 - pubs.rsc.org](#)

Graphene has intrigued the science community by many unique properties not found in conventional materials. In particular, it is the strongest two-dimensional material ever measured, being able to sustain reversible tensile elastic **strain** larger than 20%, which ...

Cited by 330 Related articles All 8 versions

[HTML] Elastic strain engineering of ferroic oxides

[DG Schlom, LQ Chen, CJ Fennie, V Gopalan... - Mrs Bulletin, 2014 - Springer](#)

Using epitaxy and the misfit **strain** imposed by an underlying substrate, it is possible to elastically **strain** oxide thin films to percent levels—far beyond where they would crack in bulk. Under such strains, the properties of oxides can be dramatically altered. In this article ...

Cited by 343 Related articles All 6 versions

Strain engineering in semiconducting two-dimensional crystals

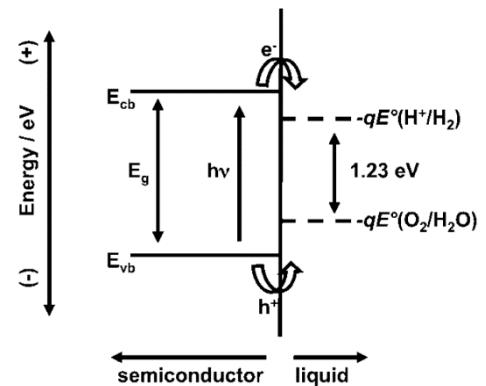
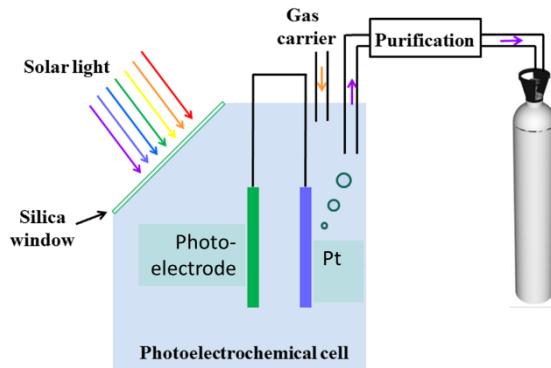
[R Roldán, A Castellanos-Gómez... - Journal of Physics ..., 2015 - iopscience.iop.org](#)

One of the fascinating properties of the new families of two-dimensional crystals is their high stretchability and the possibility to use external **strain** to manipulate, in a controlled manner, their optical and electronic properties. **Strain engineering**, understood as the field that study ...

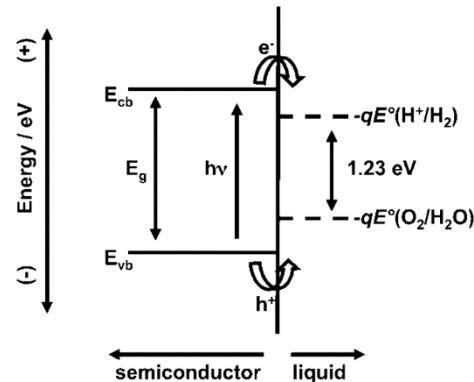
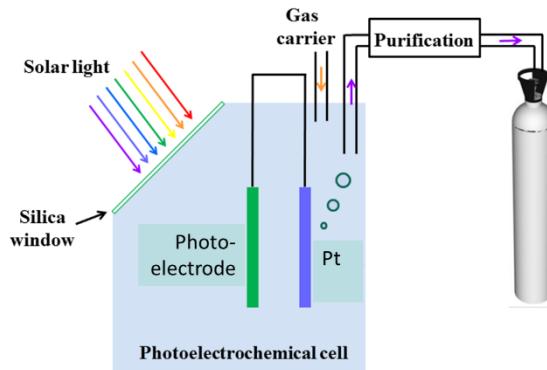
Cited by 374 Related articles All 10 versions

Outline

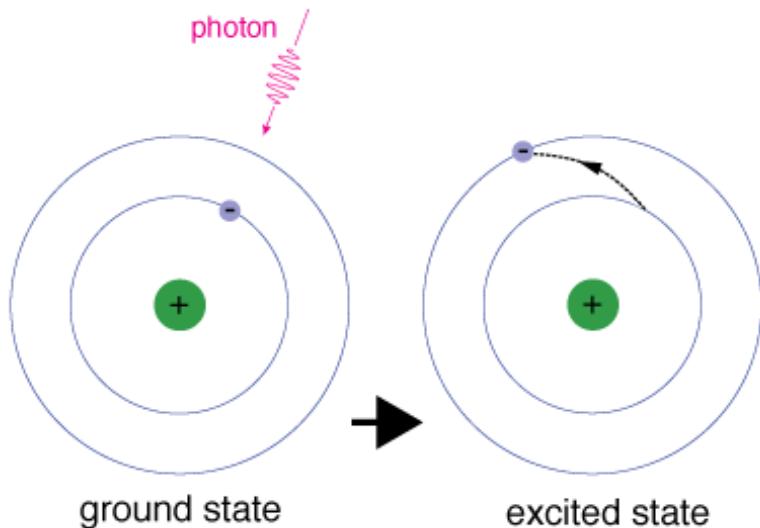
- ✓ Strategy 1: Surface Engineering of Quantum States
- ✓ Strategy 2. Strain/Stress Engineering of Quantum States
- ✓ Strategy 3. Excited State Engineering - *Tuning Exciton Structure in Carbon Nitride and Graphene Quantum Dots for Efficient Solar Energy Harvesting*
- ✓ Summary



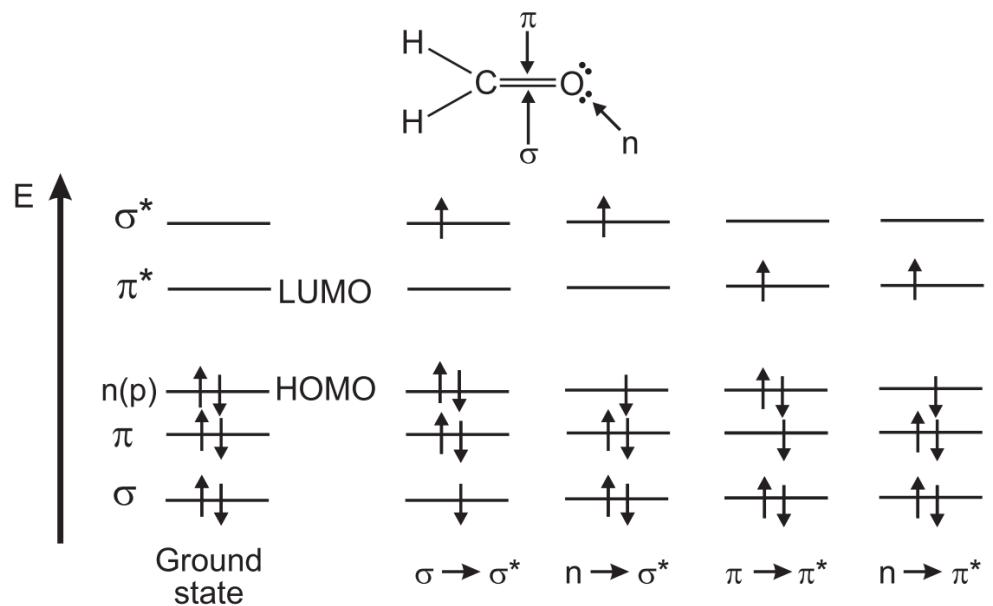
Tuning Exciton Structure in Carbon Nitride and Graphene Quantum Dots for Efficient Solar Energy Harvesting



Excitation of an atom:



Excitation of a molecule:



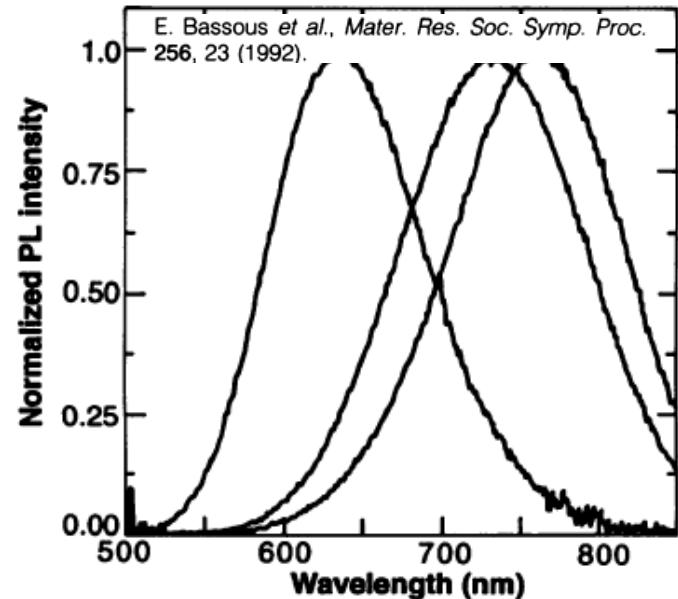
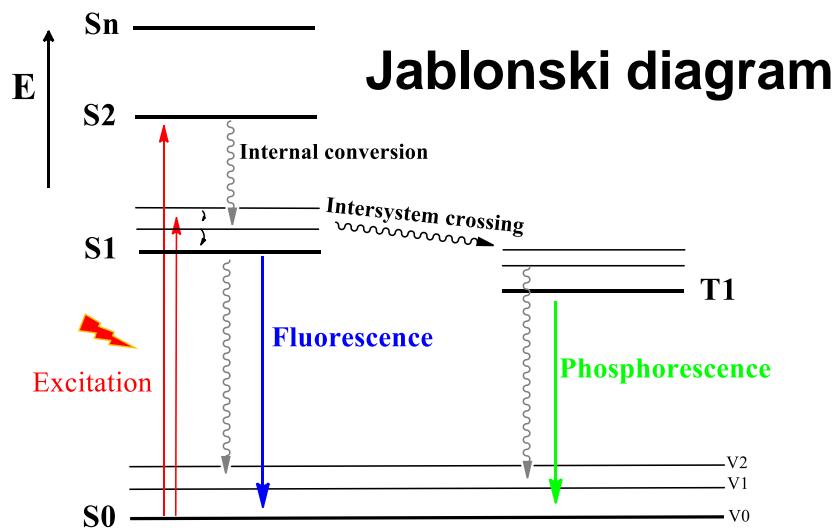
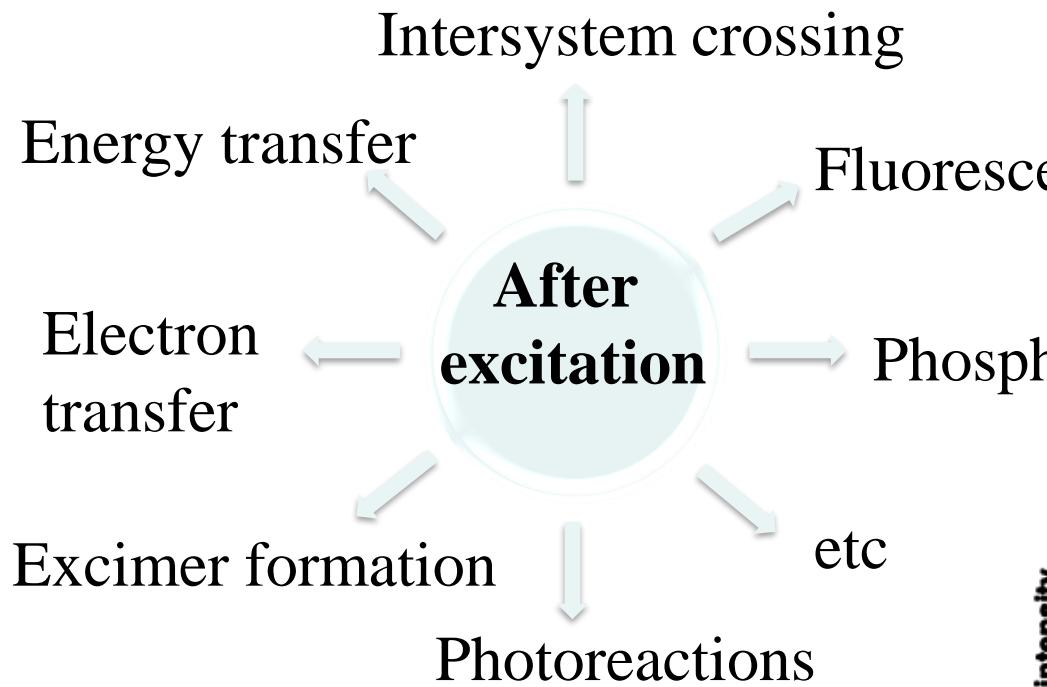
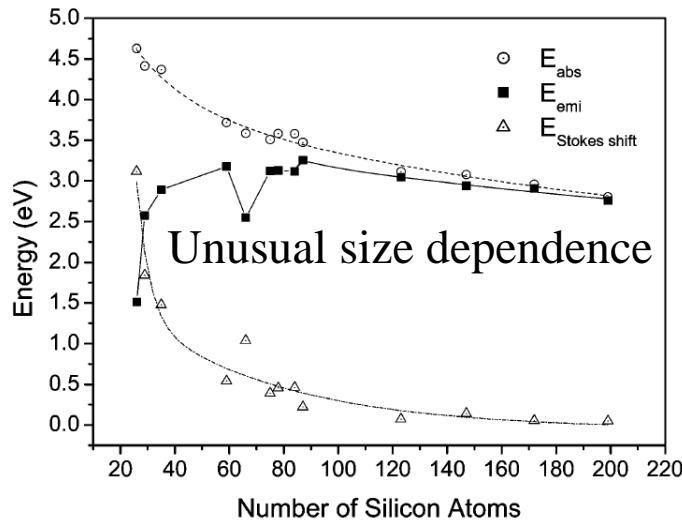
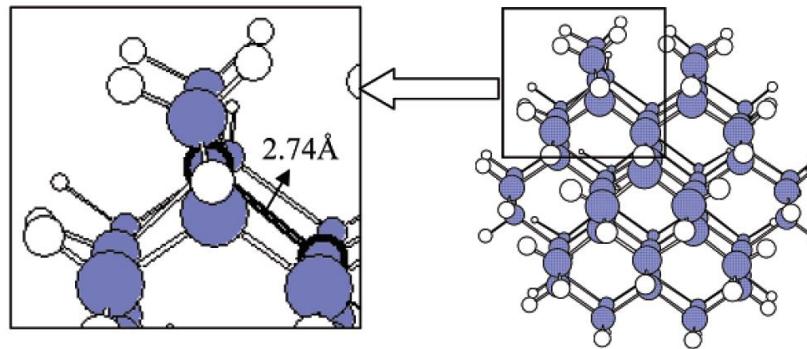


Fig. 9. Typical PL spectra for porous Si etched under different conditions. The blue shift may be a consequence of the greater confinement designers achieve by etching a finer structure (37). The incident power of the laser was 3 mW at 488 nm; experiment done in N₂.



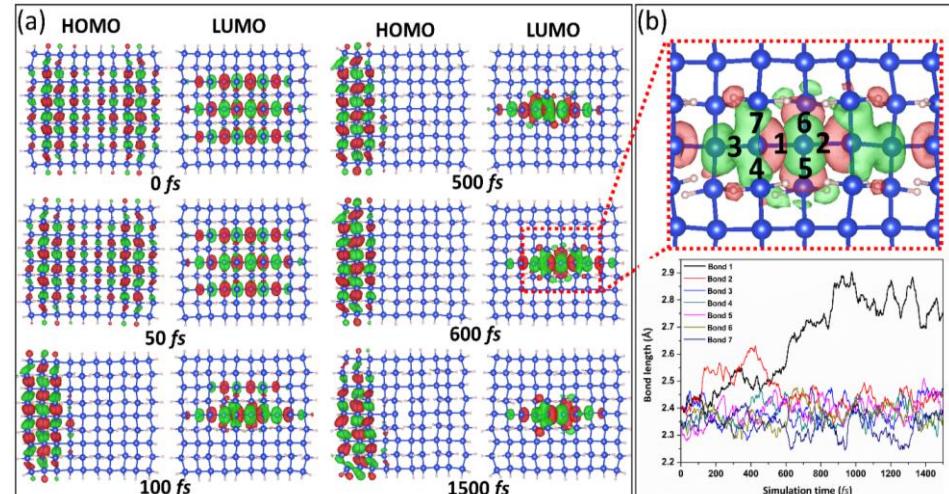
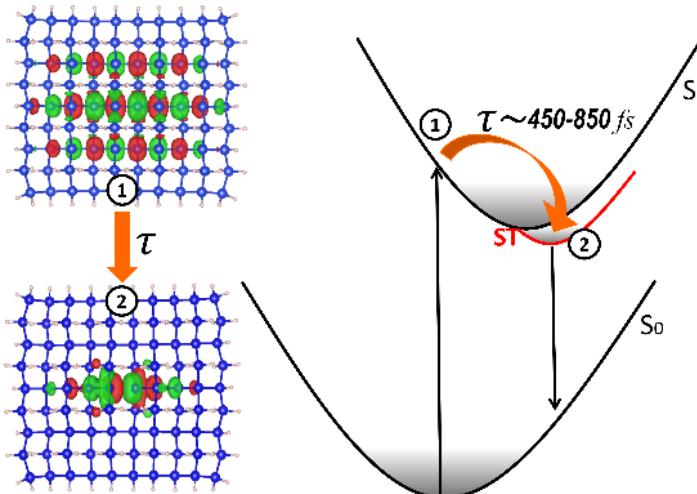
X. Wang, R.Q. Zhang*, et al. *Appl. Phys. Lett.* 90, 123116 (2007); *J. Phys. Chem. C*, 111(34); 12588-12593 (2007)



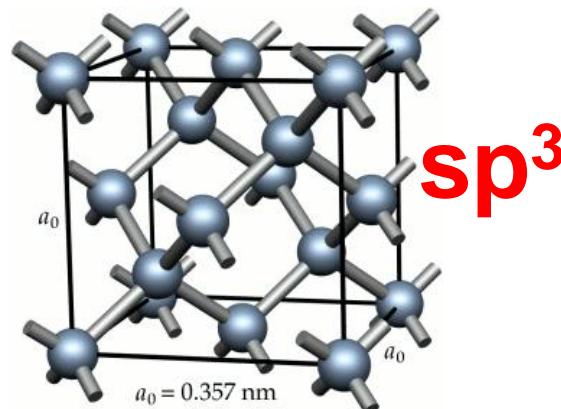
Excited state dynamics study of the self-trapped exciton formation in silicon nanosheets†

Cite this: *Phys. Chem. Chem. Phys.*,
 2018, 20, 29299

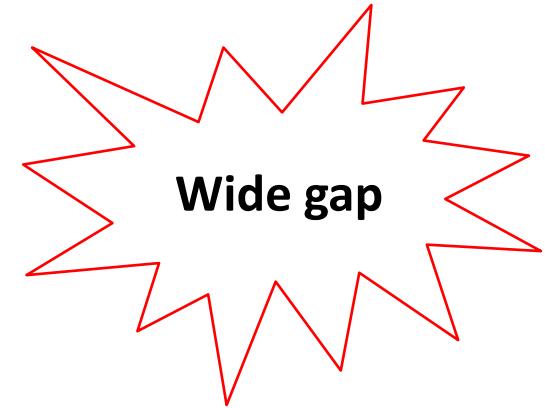
Naeem Ullah, ^a Shunwei Chen ^a and Ruiqin Zhang ^{*ab}



Diamond, Graphite and graphene



sp^3

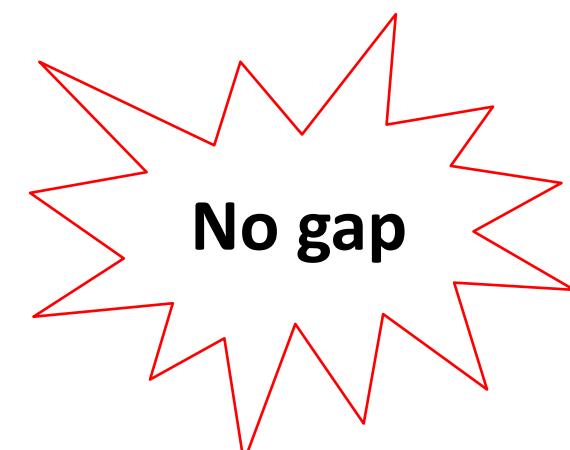
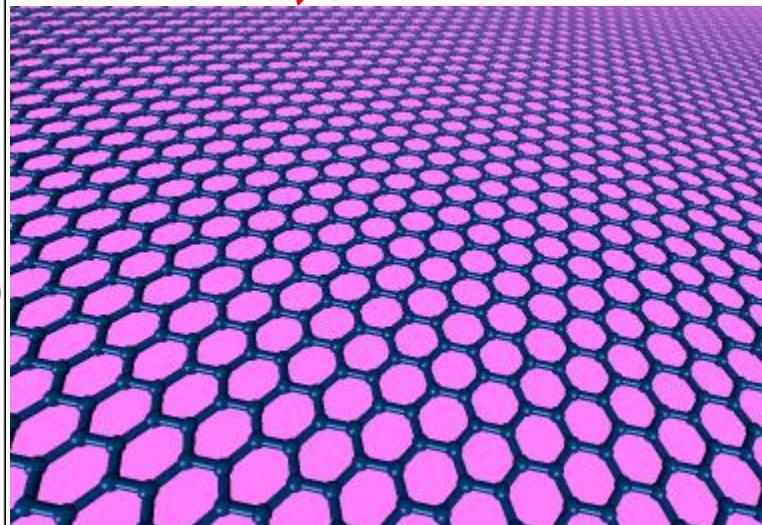


Wide gap



sp^2

graphene



No gap

The origin of the broadband luminescence and the effect of nitrogen doping on the optical properties of diamond films

L. Bergman, M. T. McClure, J. T. Glass, and R. J. Nemanich

Department of Physics and Department of Material Science and Engineering, North Carolina State University, Raleigh, North Carolina 27695-8202

3020

J. Appl. Phys. 76 (5), 1 September 1994

I. INTRODUCTION

A broadband luminescence extending from approximately 1.5 to 2.5 eV and centered at ~ 2 eV has been observed in various photoluminescence (PL) studies of diamond films grown by various chemical-vapor-deposition (CVD) methods.¹⁻⁵ In many instances this broadband PL ap-

¹J. A. Freitas, Jr., J. E. Butler, S. G. Bishop, W. A. Carrington, and U. Strom, Mater. Res. Soc. Symp. Proc. 162, 237 (1990).

²D. S. Knight and W. B. White, Proc. SPIE 1055, 144 (1989).

³E. S. Etz, E. N. Farabaugh, A. Feldman, and L. H. Robins, Proc. SPIE 969, 86 (1988).

⁴J. A. Freitas, Jr., J. E. Butler, and U. Strom, J. Mater. Res. 5, 2502 (1990).

⁵L. H. Robins, E. N. Farabaugh, and A. Feldman, Proc. SPIE 1325, 130 (1990).

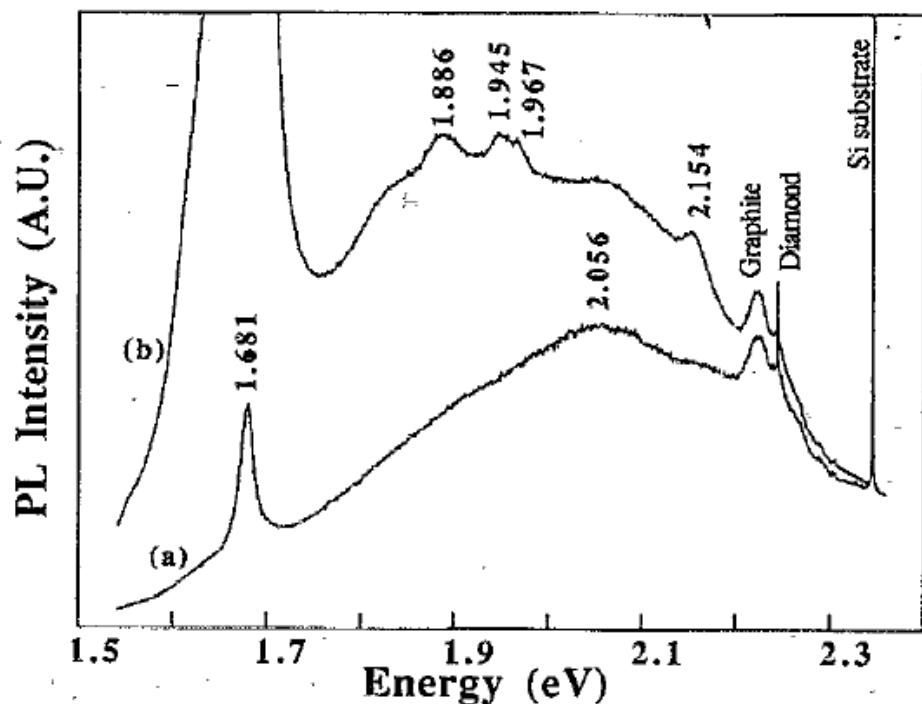


FIG. 2. The PL spectra of (a) 0% nitrogen sample and (b) of 0.1% nitrogen-doped sample employing the 514.5-nm laser line. Raman bands are labeled as to origin and the peak energy of the PL bands are indicated.

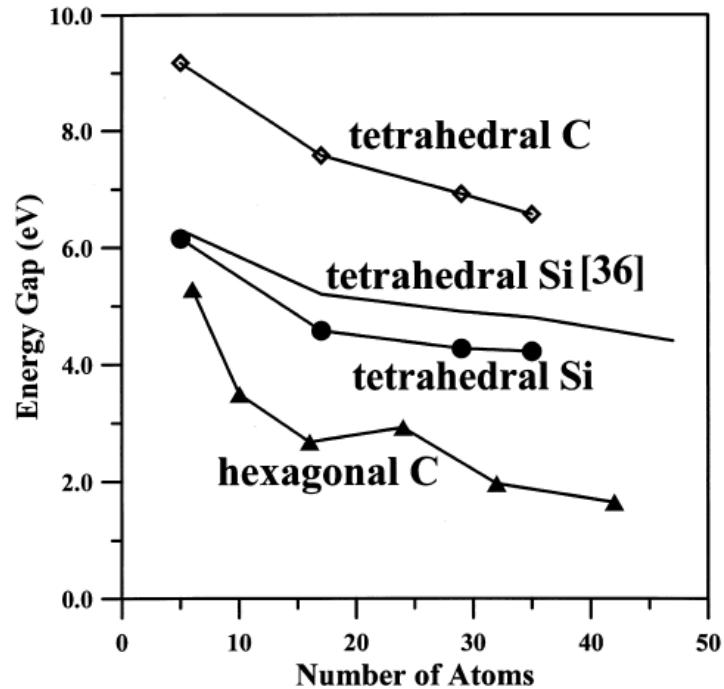
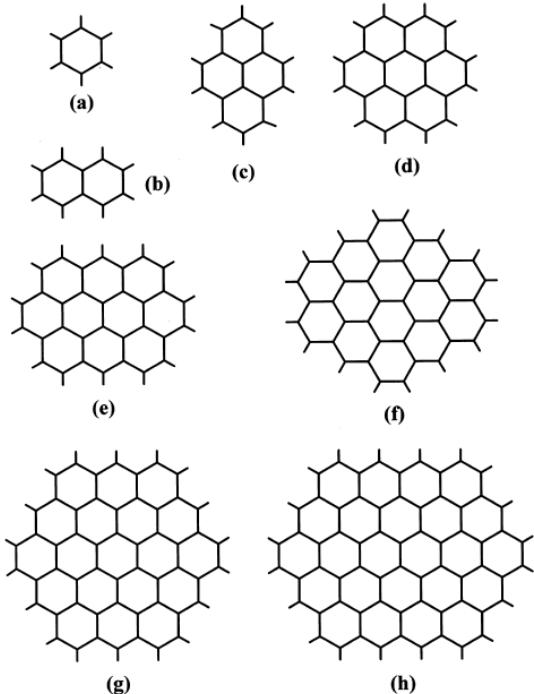
Size dependence of energy gaps in small carbon clusters: the origin of broadband luminescence

R.Q. Zhang ^{a,b,*}, E. Bertran ^a, S.-T. Lee ^b

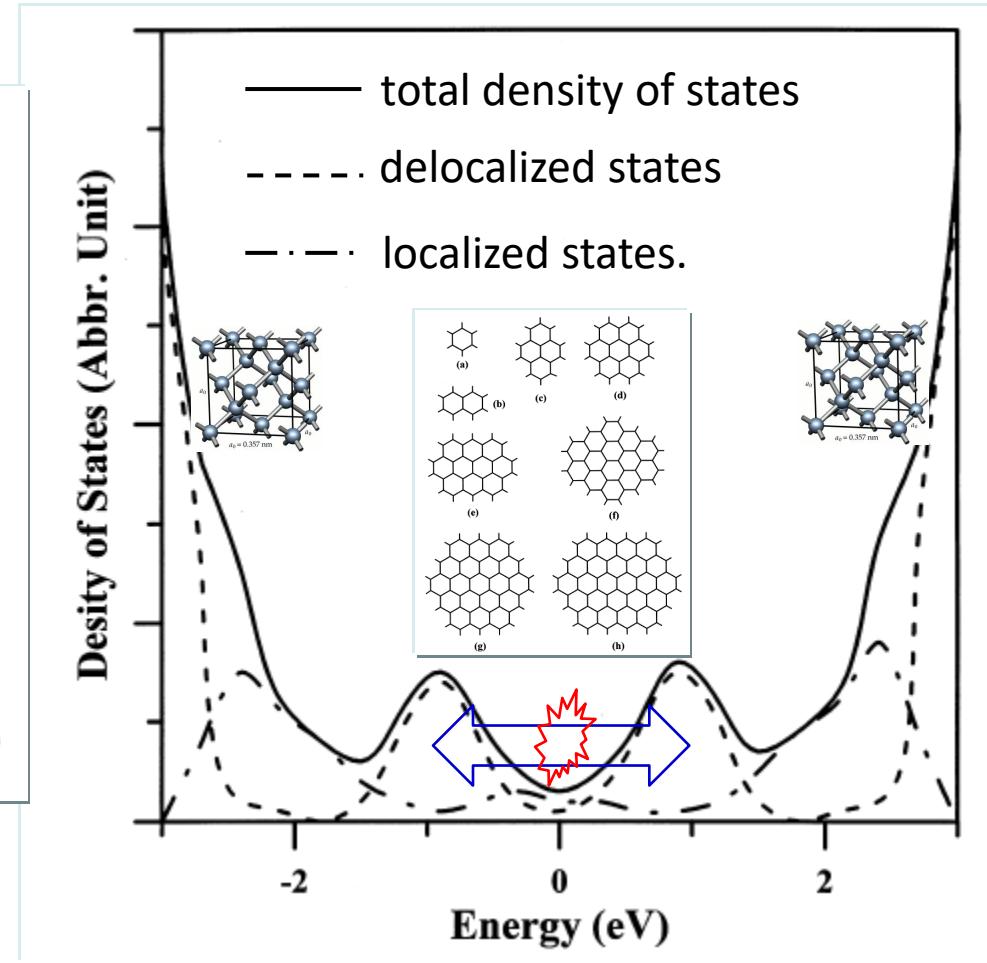
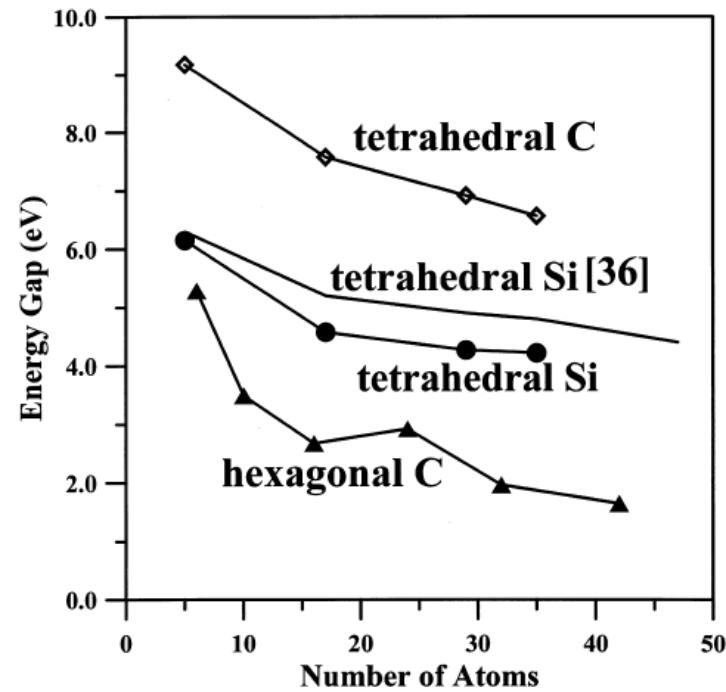
^a Departament de Física Aplicada i Electrònica, Universitat de Barcelona, Av. Diagonal 647, E08028 Barcelona, Spain

^b Department of Physics and Materials Science, City University of Hong Kong, Kowloon, Hong Kong

Received 4 February 1998; accepted 14 August 1998

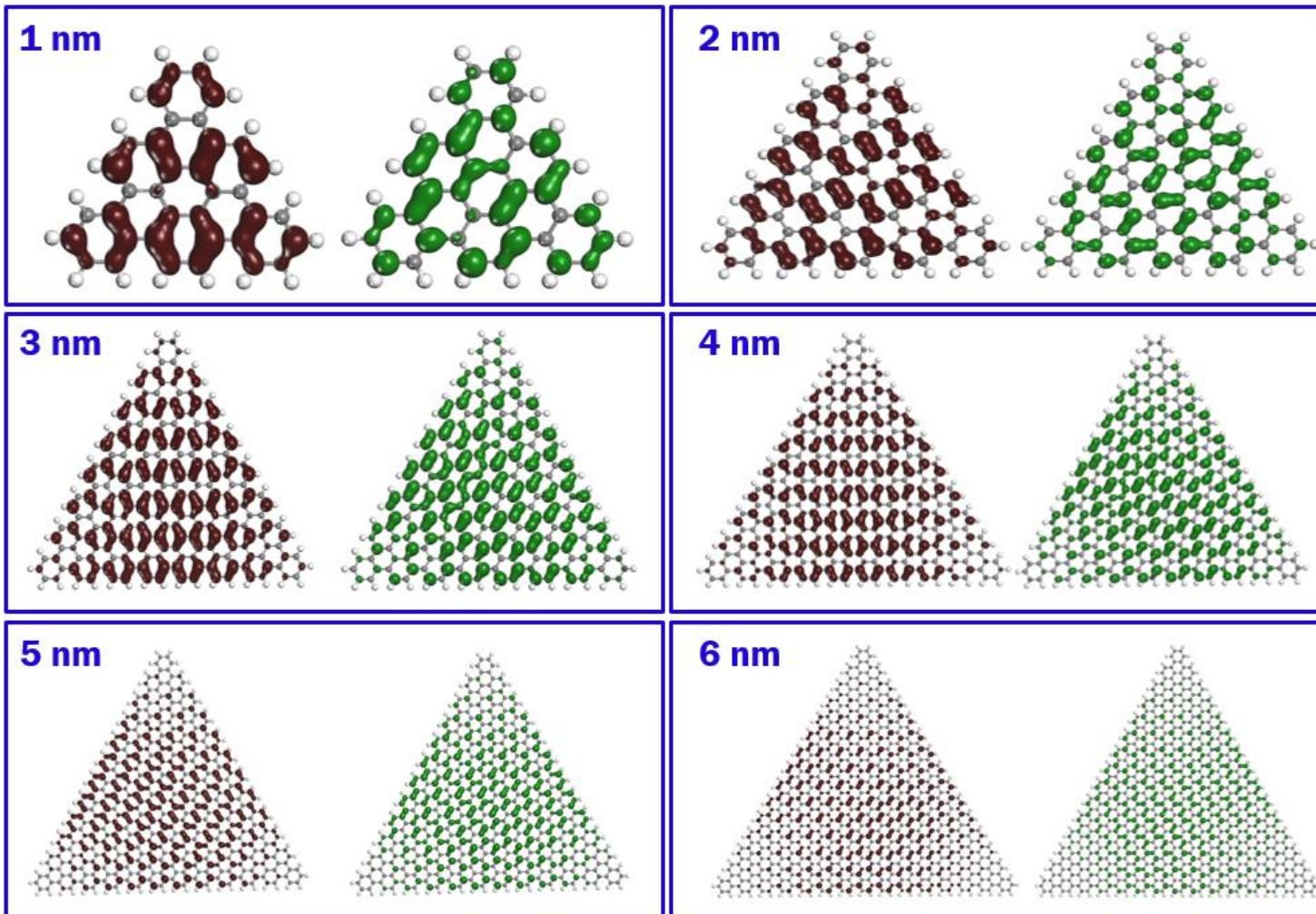


Interpretation of broadband PL from a-C



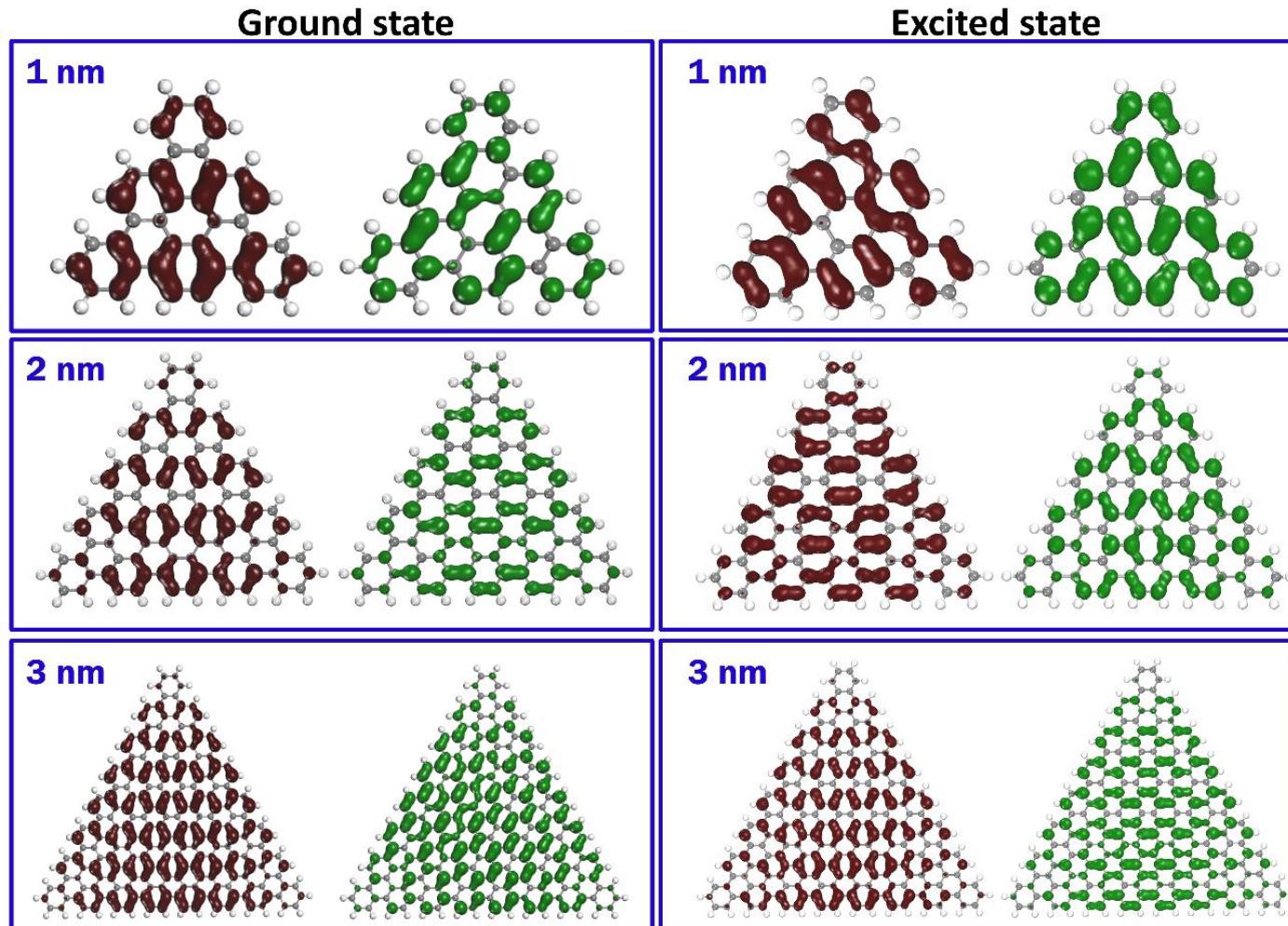
R.Q. Zhang*, E. Bertran, and S.-T. Lee "Size-dependence of energy gaps in small carbon clusters: the origin of broadband luminescence",
Diamond and Related Materials, 7, 1663(1998)

Carrier separation vs size – GQDs



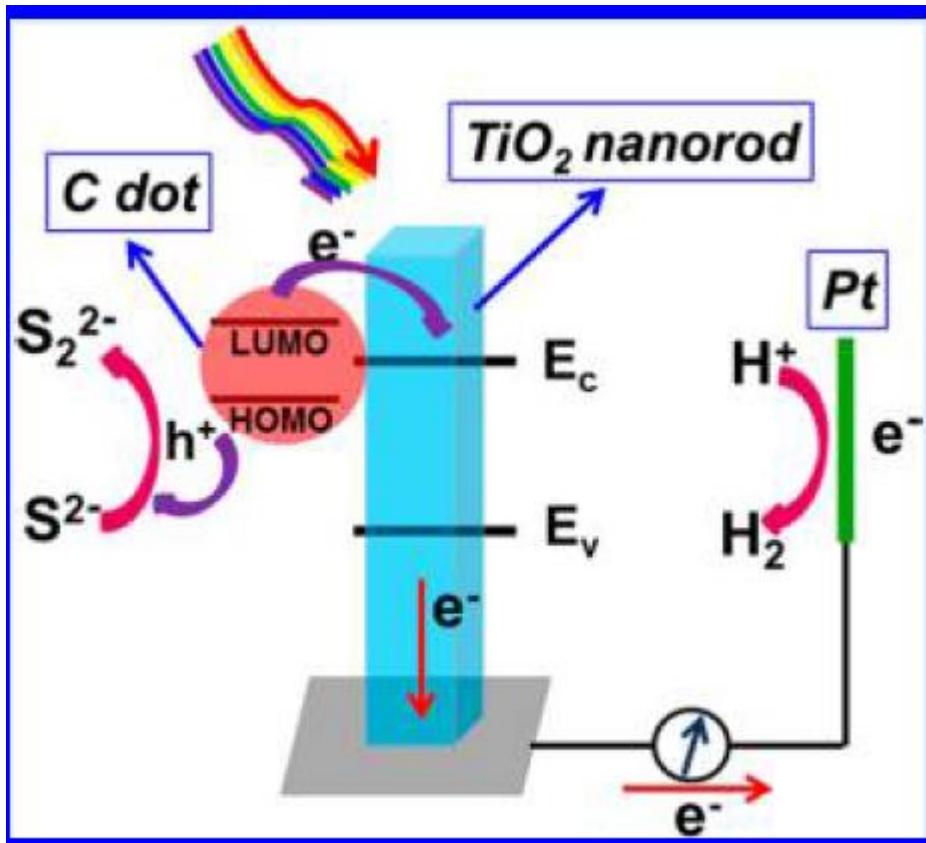
Ground state: Dark brown (dark green) - HOMO (LUMO)

Carrier separation vs size – GQDs

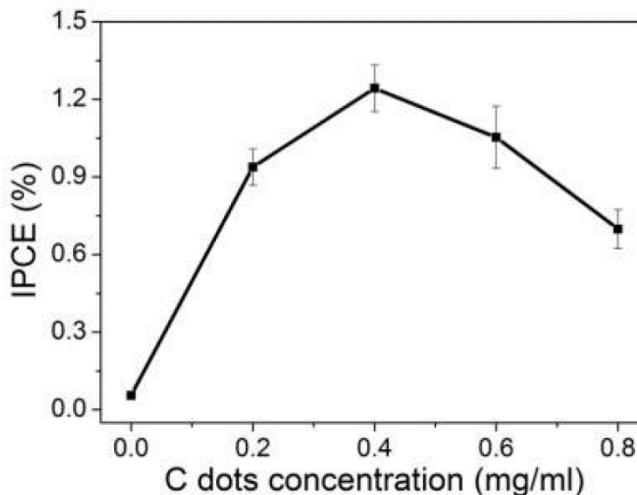


ACS Appl. Mater. Interfaces 2014, 6, 4883–4890

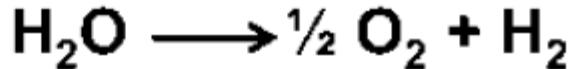
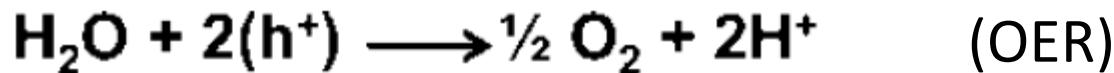
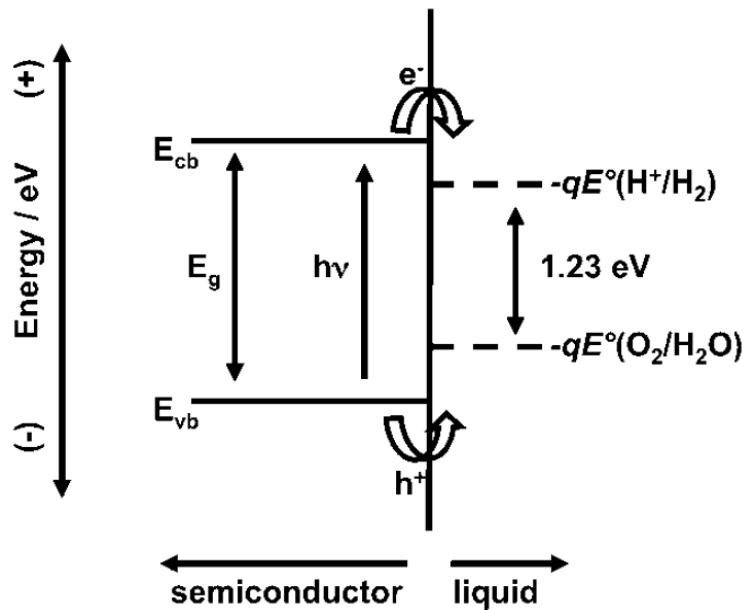
Carbon Dot Loading and TiO_2 Nanorod Length Dependence of Photoelectrochemical Properties in Carbon Dot/ TiO_2 Nanorod Array Nanocomposites

Juncao Bian,[†] Chao Huang,[†] Lingyun Wang,[‡] TakFu Hung,[†] Walid A. Daoud,[‡] and Ruiqin Zhang^{*,†}

The incident photon to current conversion efficiency (IPCE) of the TNRA/C dot nanocomposites in the visible range was up to 1.2–3.4%.

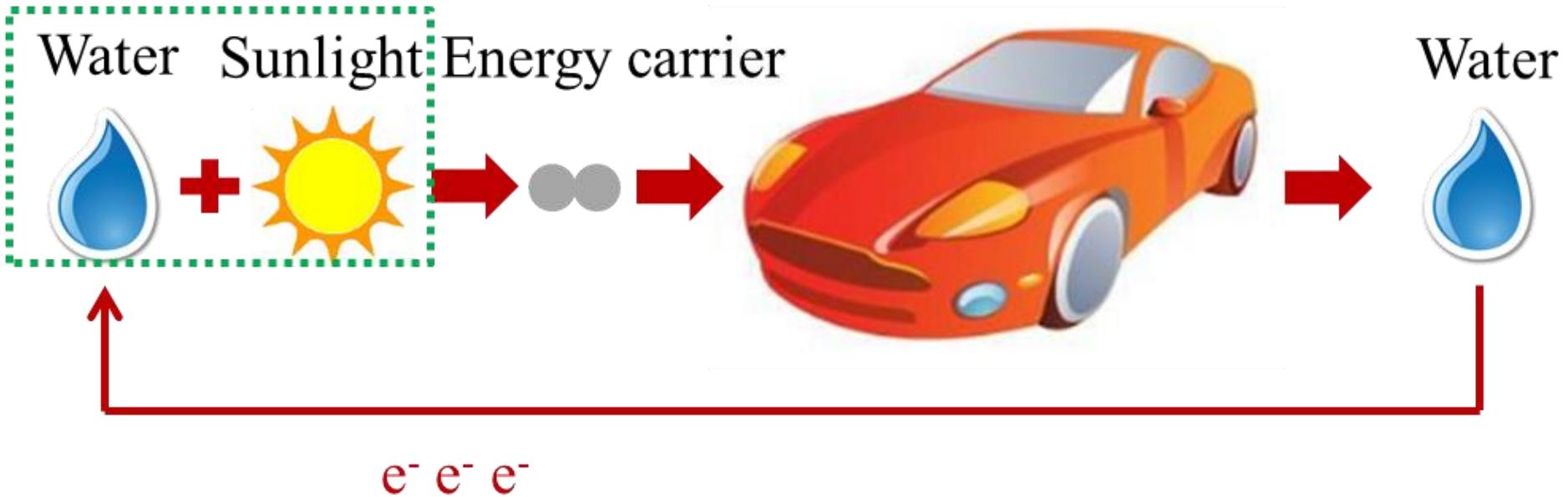
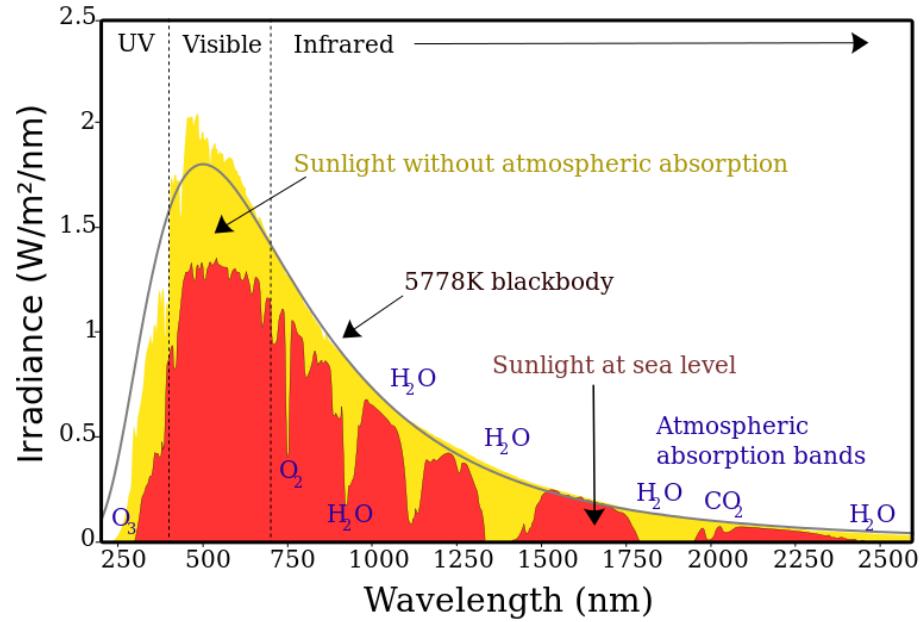


Water splitting





Spectrum of Solar Radiation (Earth)

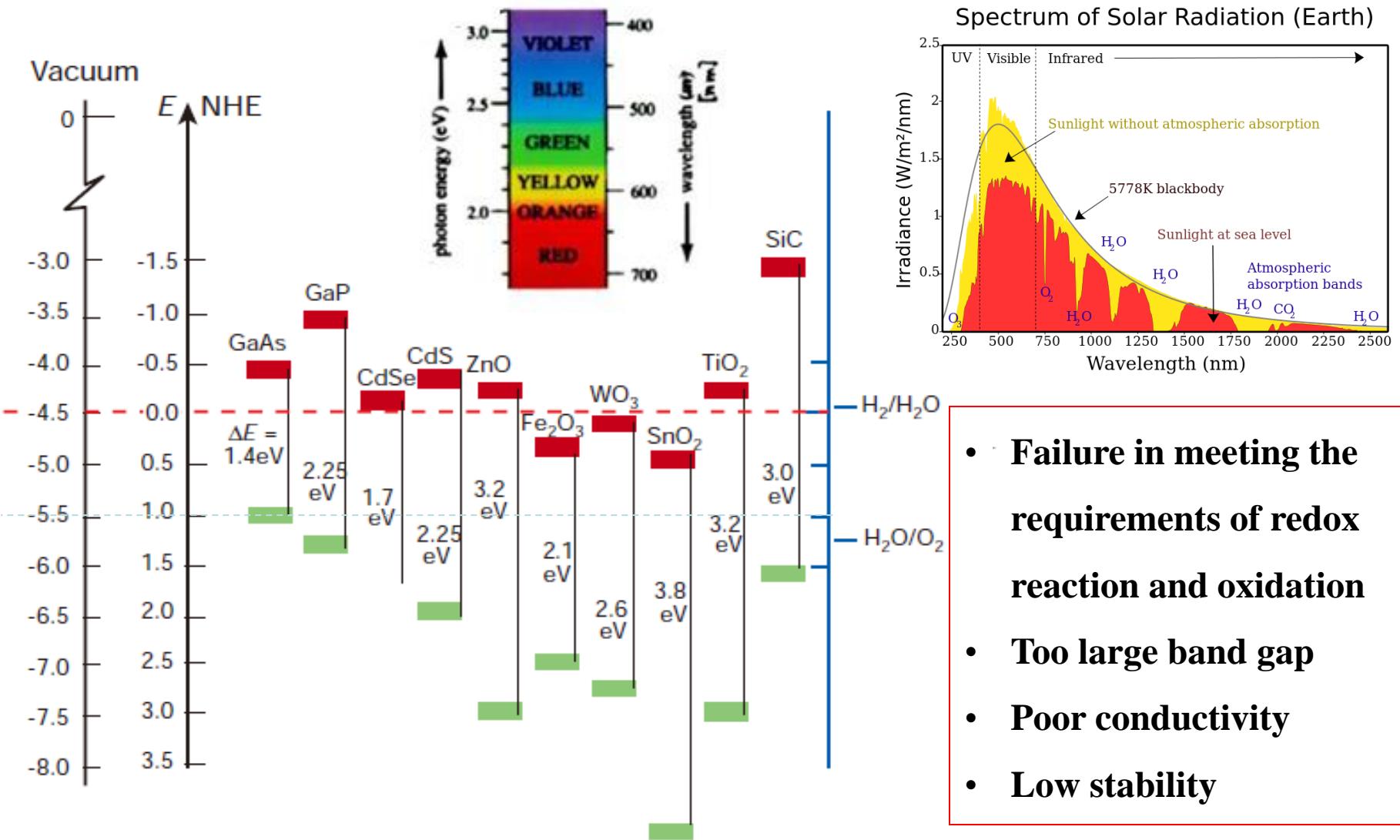


H₂ generation, solar cell, lithium ion battery, fuel cell battery ...
- green energy approaches

Rising cost of oil and environmental challenges forced India and China to take various steps.



Drawbacks of conventional photocatalytic materials

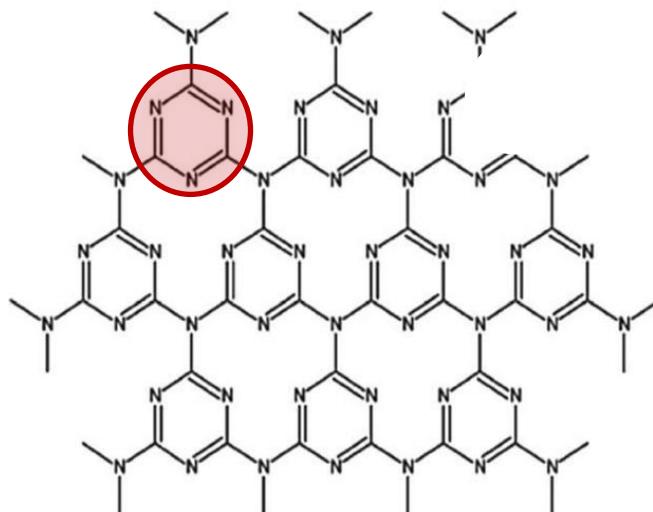


Michael Grätzel, "Photoelectrochemical cells", *Nature*, 44, 338 (2001).

Graphitic carbon nitride ($\text{g-C}_3\text{N}_4$)

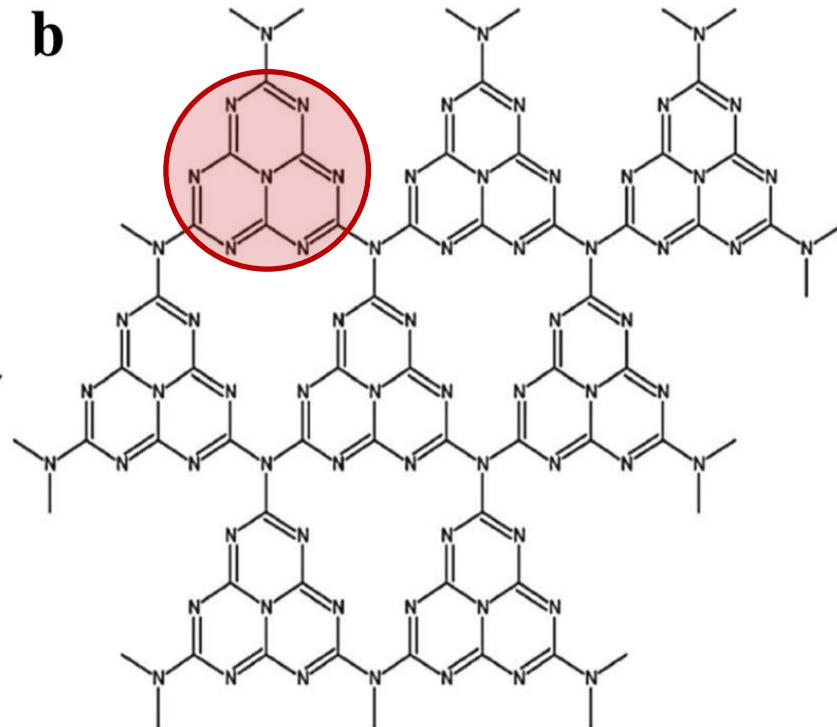
Trizine

a

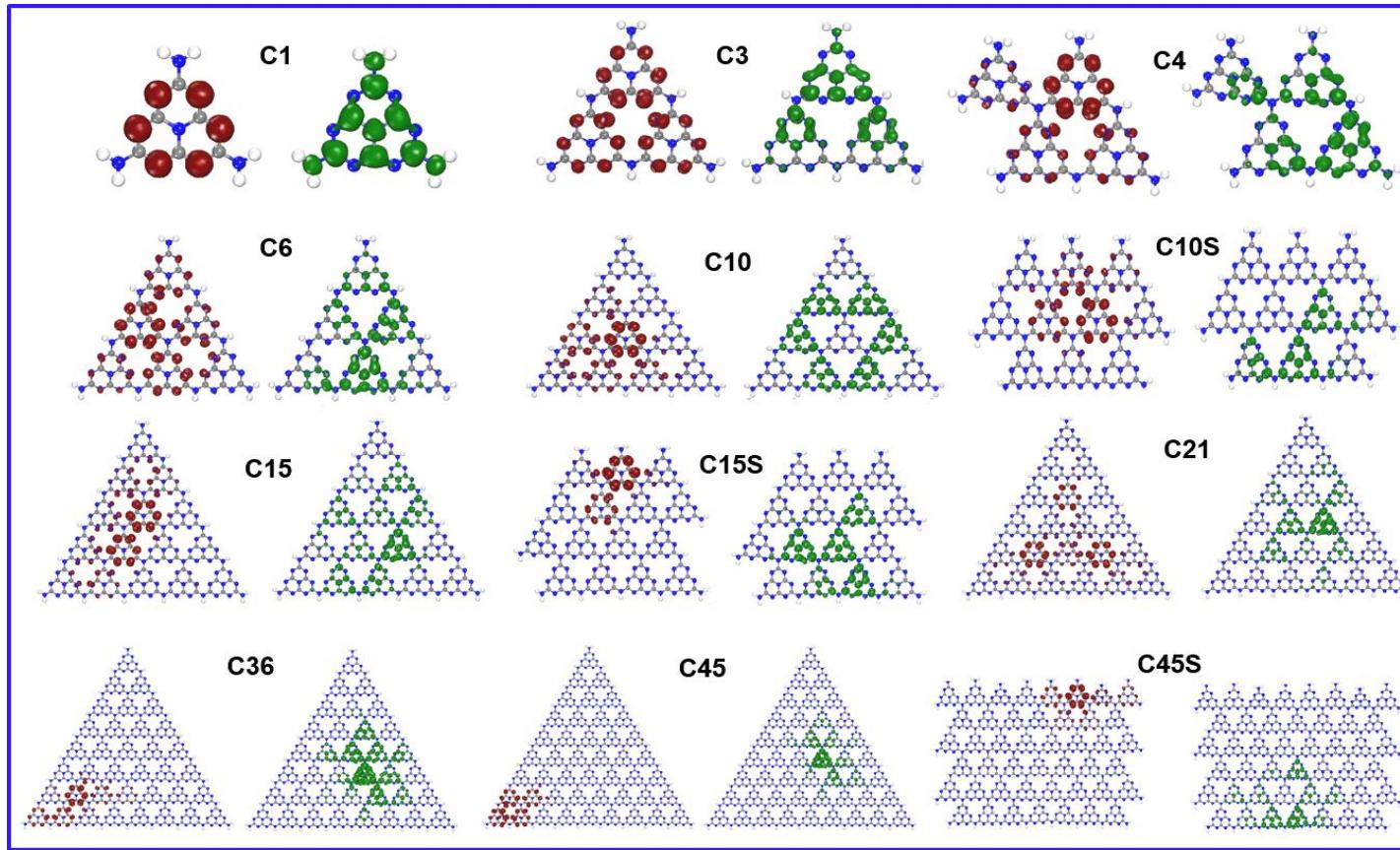


Tri-s-trizine

b

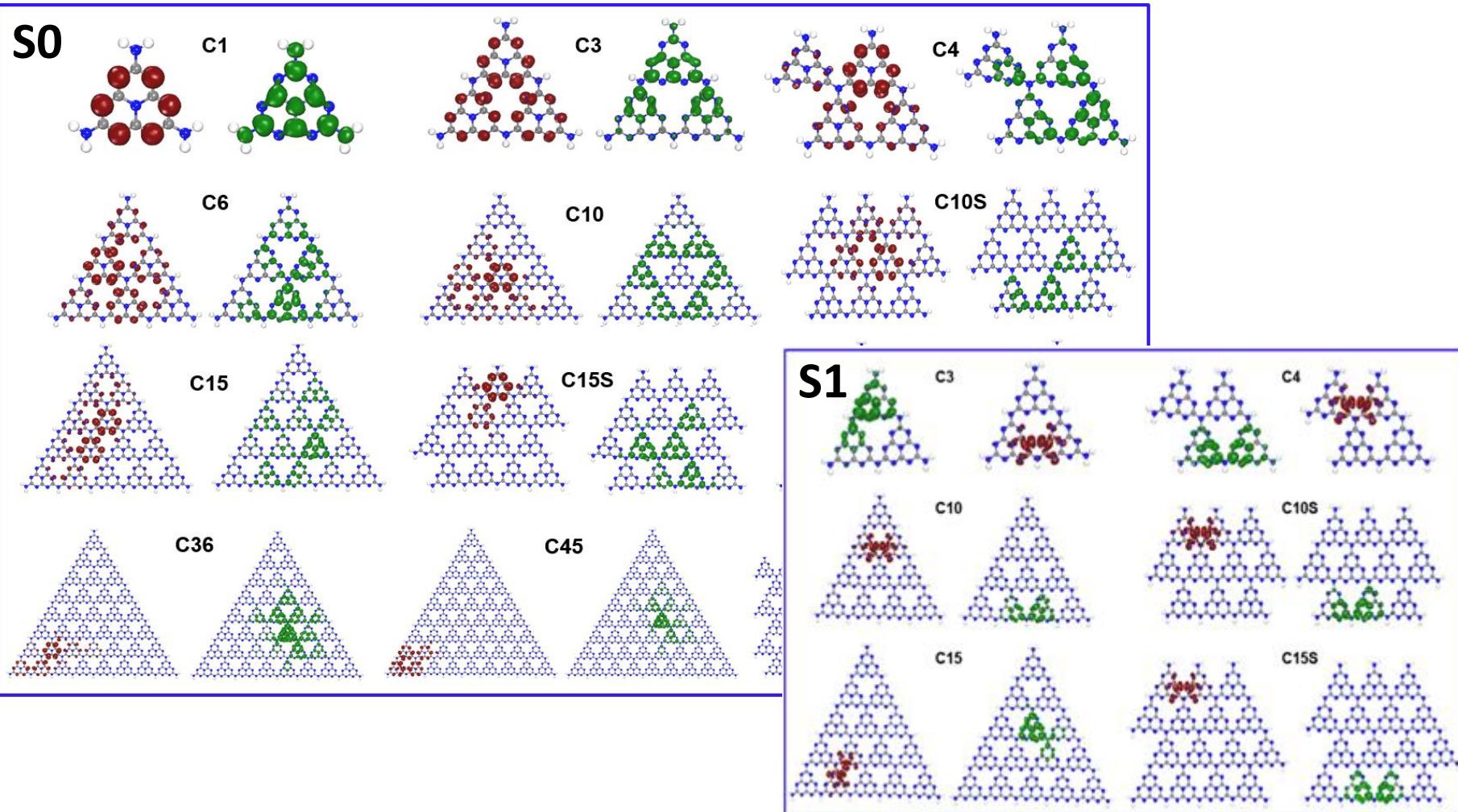


Carrier separation vs size - CNQDs



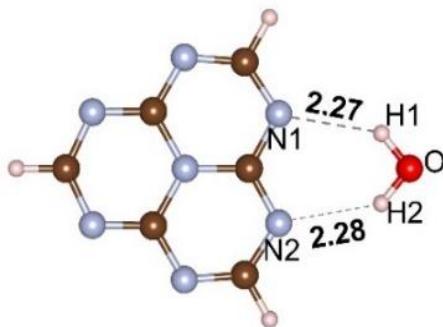
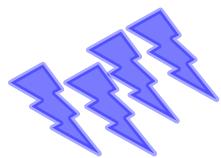
Ground state: Dark brown (dark green) - HOMO (LUMO)

S0 vs S1 - CNQDs

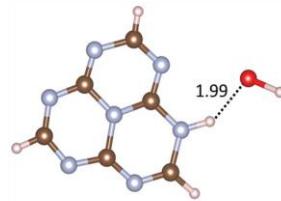


Excited-state non-adiabatic dynamics simulations of heptazine with one water molecule

Ullah, Chen and Zhang, *JPCL*(2019)



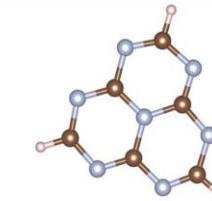
TDDFT dynamics results



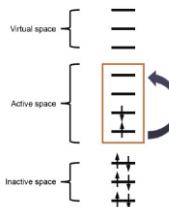
$S_1 - S_0$ difference 0.09 eV
(Threshold ~0.15 eV)

ω B97XD 6-31G(d,p)

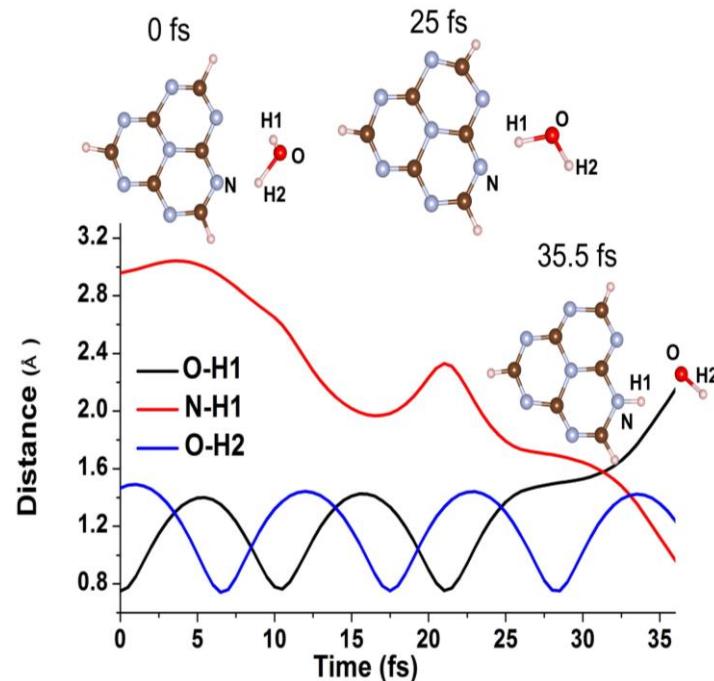
CASSCF optimization results



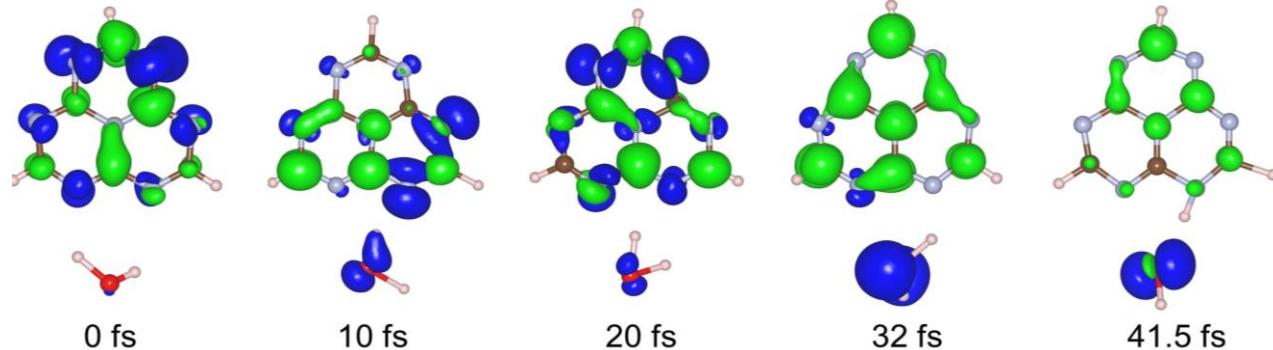
$S_1 - S_0$ difference 0.002 eV



Water-heptazine hydrogen transfer



Revealed a barrier of 0.68 eV (0.75 eV by ADC(2)).

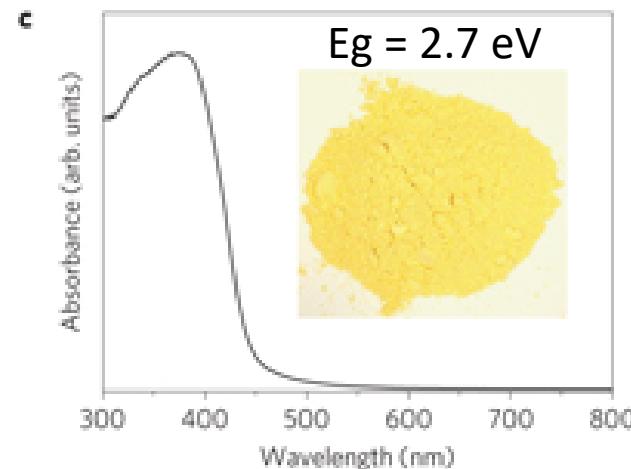
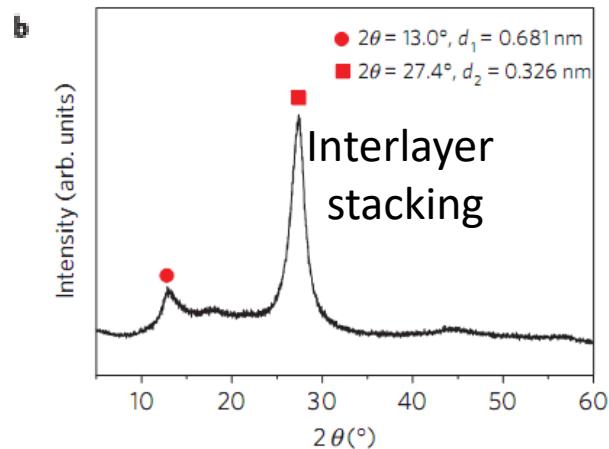
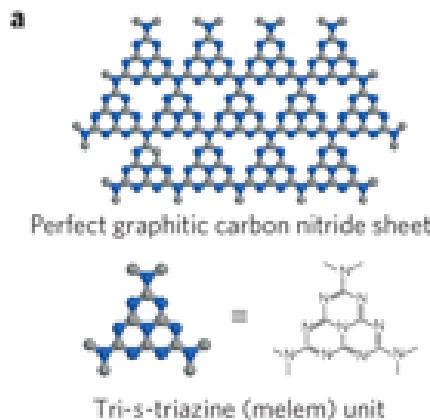


fs resolved
electron-hole
map

Electron-driven proton transfer (EDPT) found to be the cause for non-radiative decay.

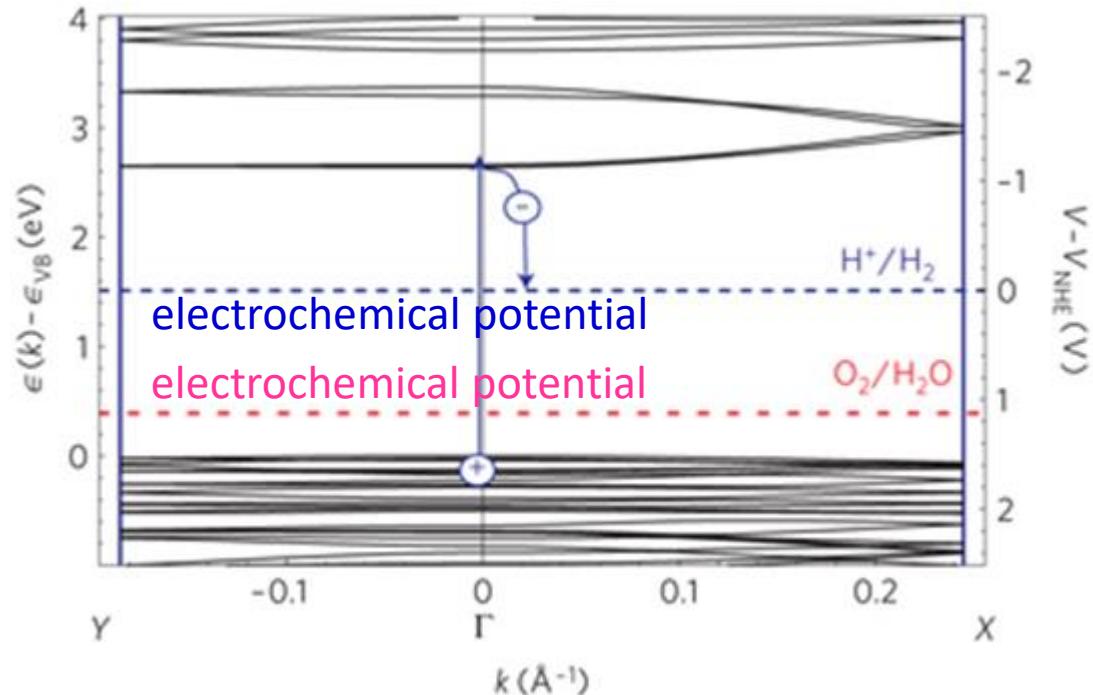
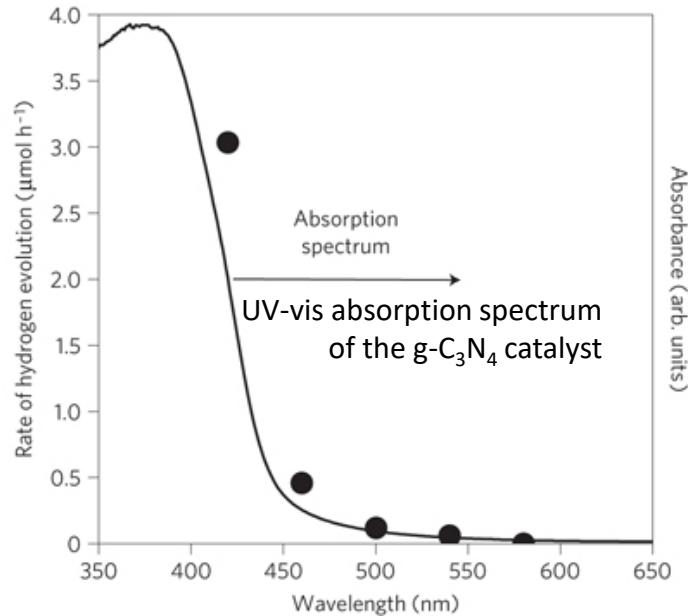
Graphitic carbon nitrides ($\text{g-C}_3\text{N}_4$) - a metal-free polymeric photocatalyst for hydrogen production from water under visible light

Wang, X. C.; Maeda, K.; Thomas, A.; Takanabe, K.; Xin, G.; Domen, K.; Antonietti, M.
Nat. Mater. **2009**, *8*, 76–82



- a, A perfect graphitic carbon nitride sheet constructed from melem units.
- b, XRD pattern of the g-CN: interplanar stacking distance (0.326 nm).
- c, UV-vis diffuse reflectance spectrum.

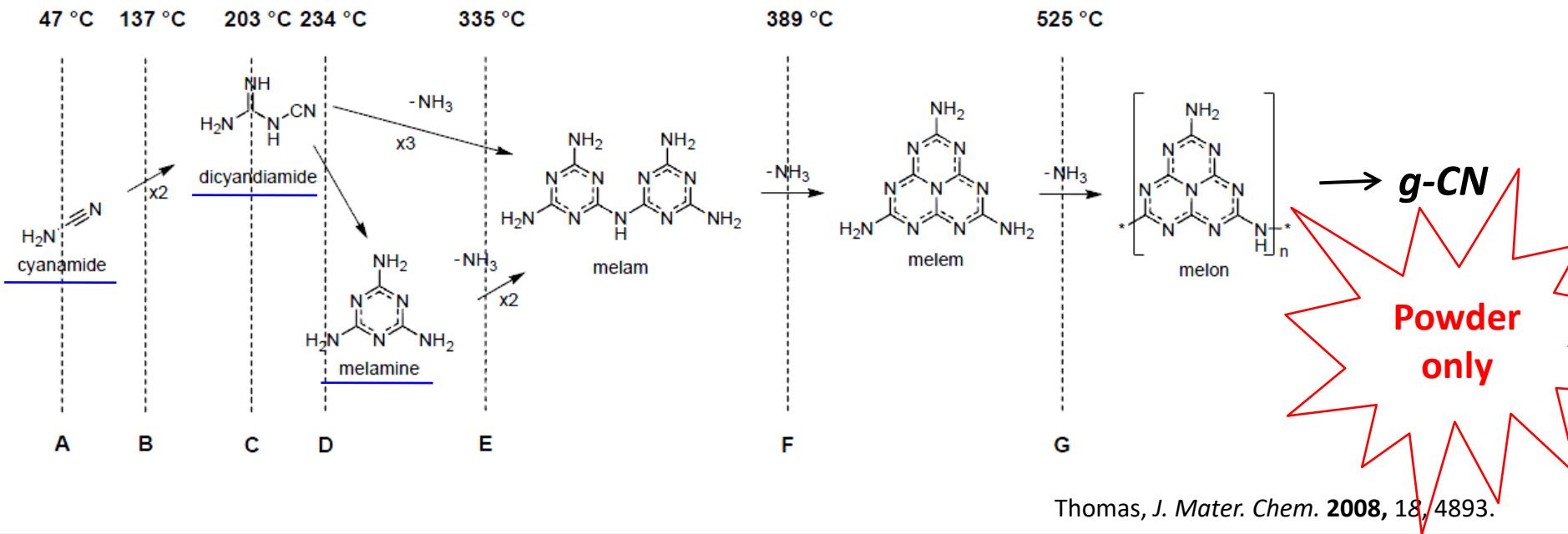
DFT band structure for polymeric melon



Steady **rate of H_2 production** from water containing 10 vol% methanol as an electron donor by 0.5 wt% Pt-deposited $\text{g-C}_3\text{N}_4$ photocatalyst

Synthesis of g-CN powder

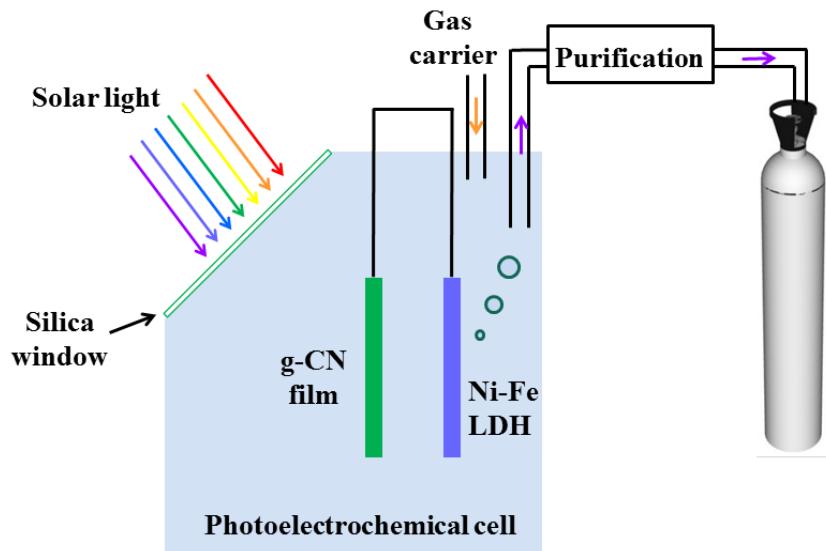
Thermal Polymerization



- A combination of polyaddition and polycondensation
- **Other monomers:** melamine, urea, thiourea, ...

PEC

A. Fujishima and K. Honda,
Nature, 1972, 238, 37–38



Advantages od PEC:

- 1) small backward reaction
- 2) easy to collect H₂ and O₂
- 3) small bias voltage

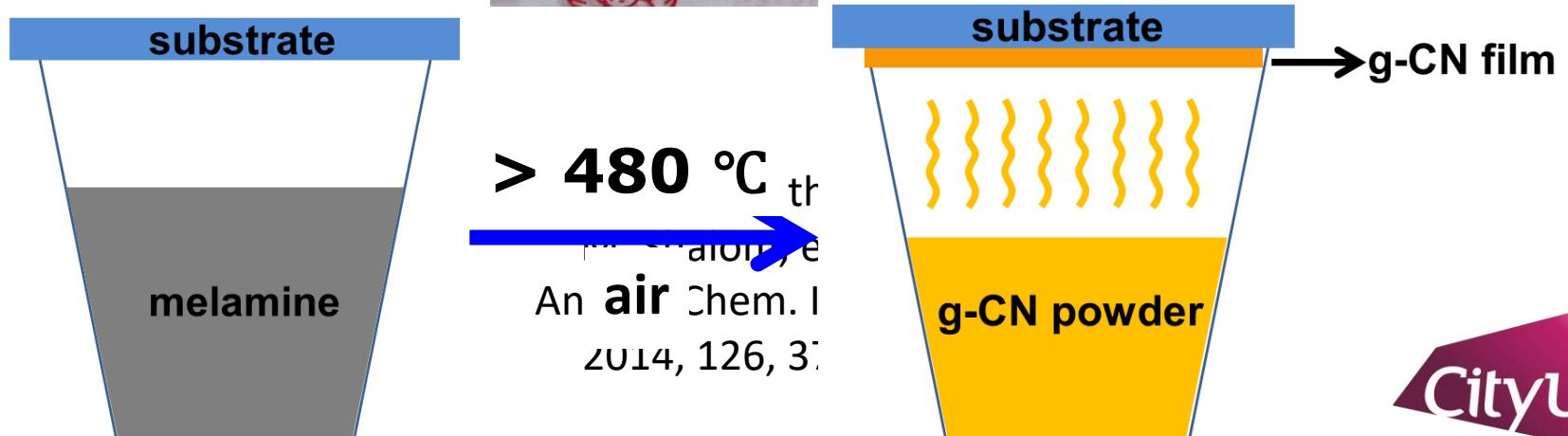
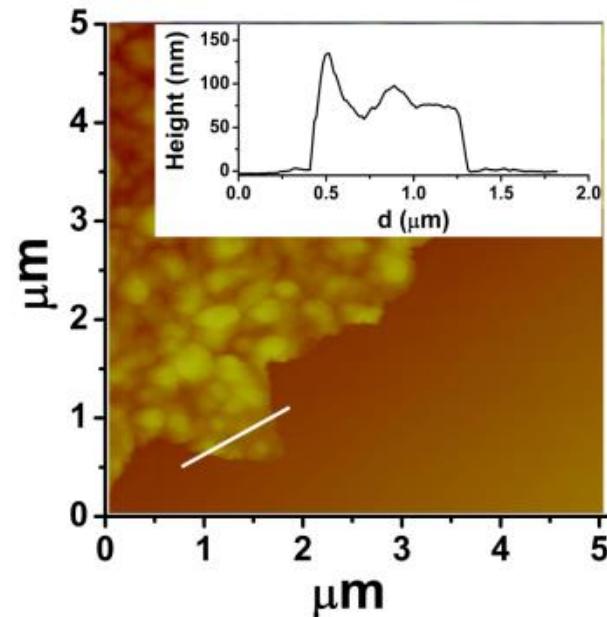
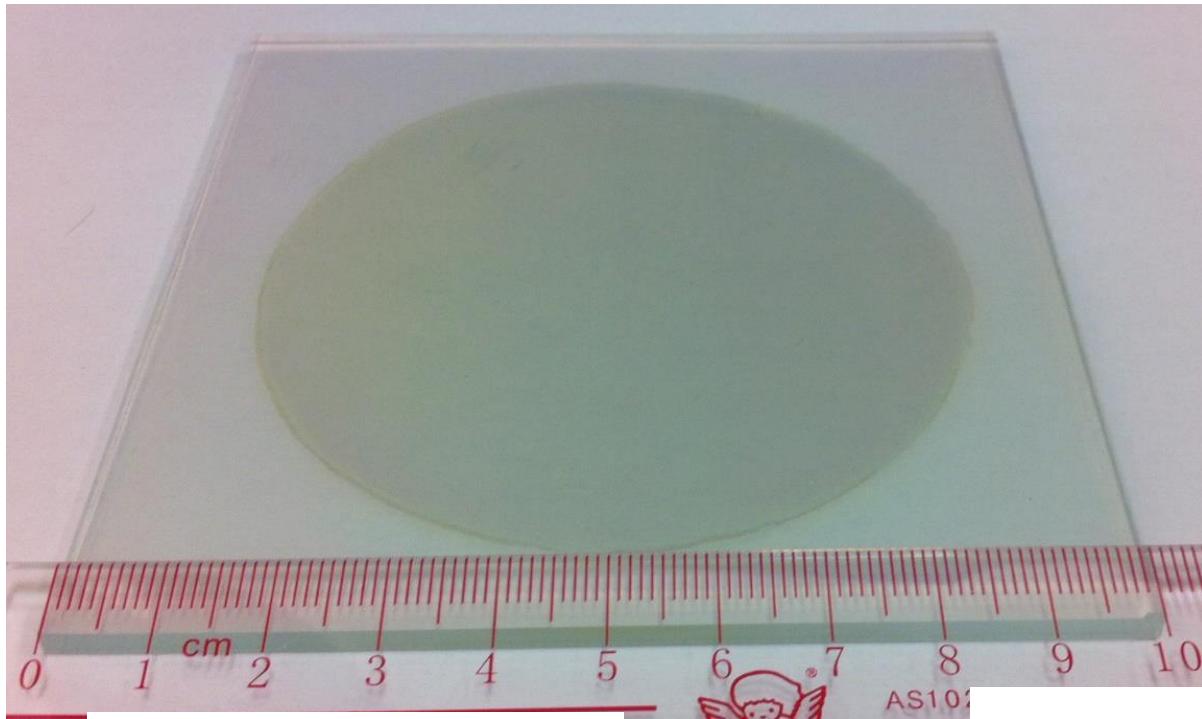
Prerequisite:

- ✓ substrate supported film
- ✓ uniform and pinhole free
- ✓ large area synthesis

Difficulties in growing thin films from powder:

- insoluble in most solvents
- conventional methods (spin coating, drop casting, doctor blade) not working well

Our thermal vapor condensation method vs others



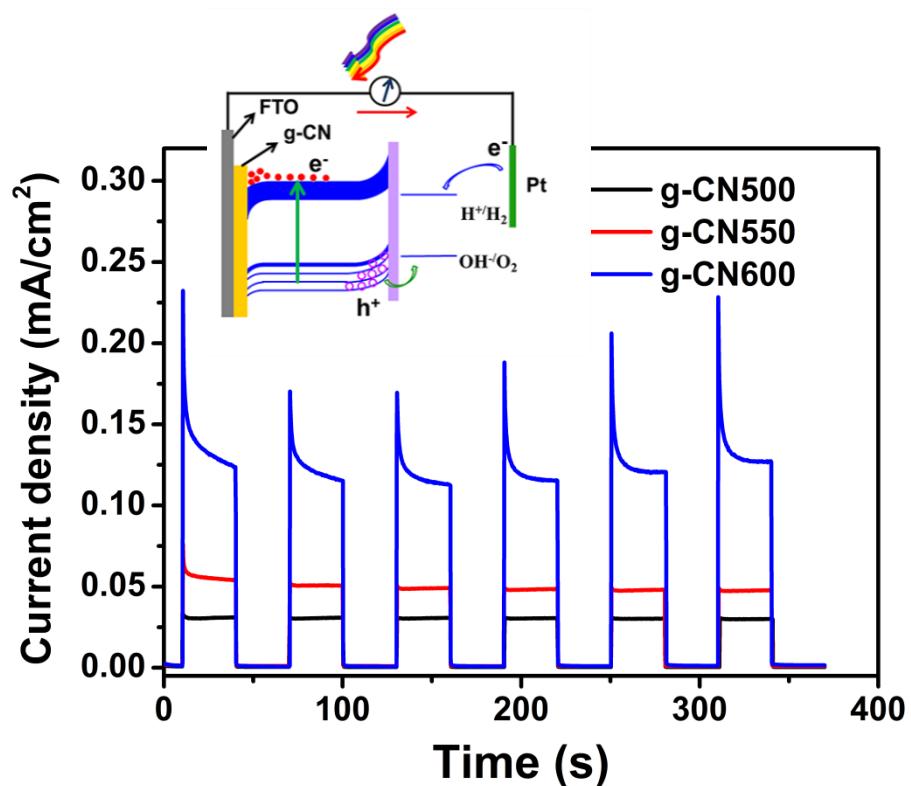
> 480 °C_{tr}
pyrolysis, e
air Chem. I
2014, 126, 31

Our films

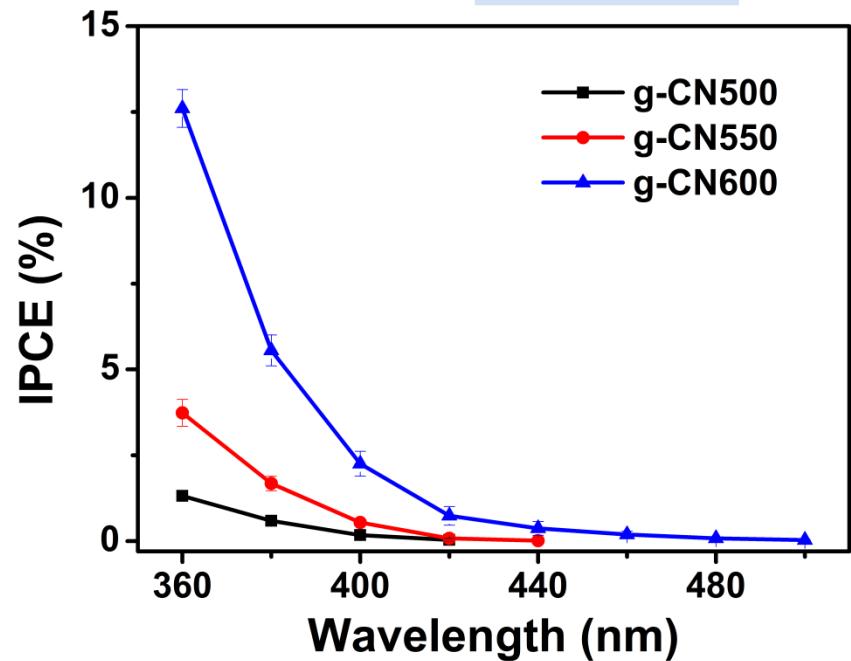
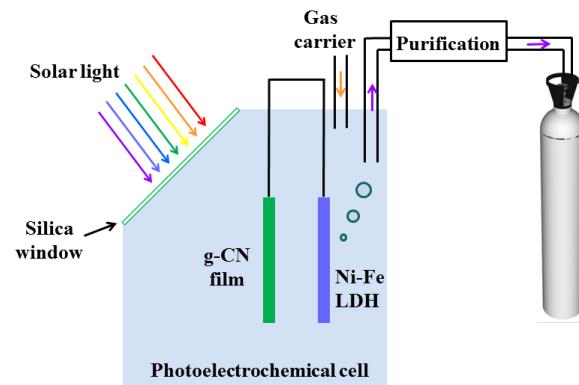
1. uniform, adjustable area
2. adjustable thickness: tens to hundred nanometers
3. easy to control the morphology
4. tunable electrical and optical properties by doping

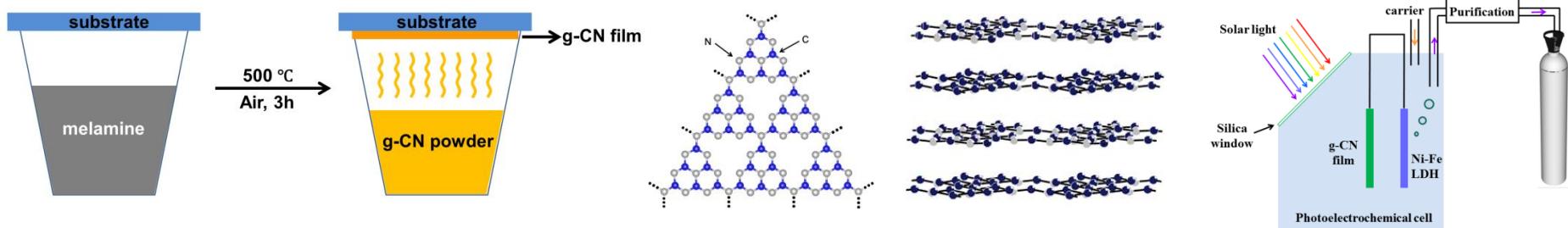
Zhang and Bian, “A thermal vapor condensation method of graphitic carbon nitride films” **US Patent (filed, 2016)**, published in 2018

Transient photocurrent and incident photon conversion efficiency



AM 1.5, 0.12 mA/cm^2 at 0.5 V vs Ag/AgCl, $\text{Na}_2\text{SO}_4 + \text{Na}_2\text{SO}_3 + \text{Na}_2\text{S}$





Photocurrent density of 0.12 mA/cm^2 under one sun illumination at 1.55 V versus reversible hydrogen electrode (RHE)

Need further improvements on:

- photocurrent density
- light absorption in the visible range
- diffusion length of charge carrier
- charge transfer of electrons and holes

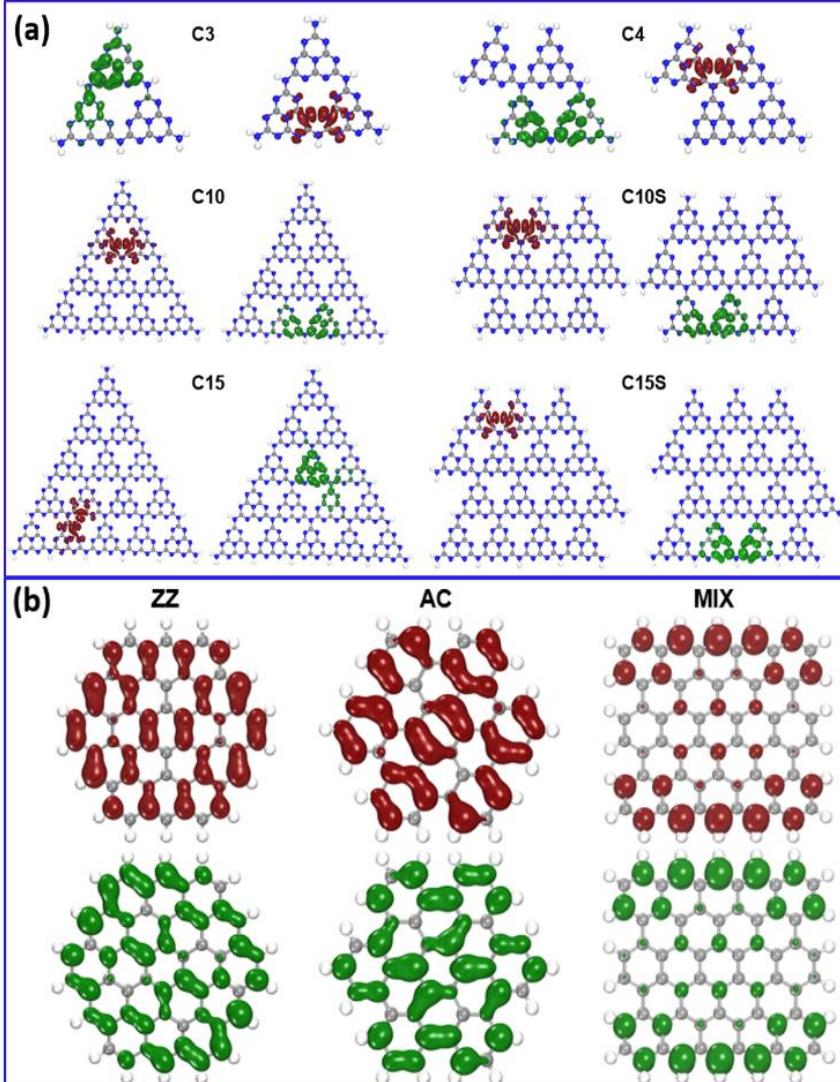
Perfect carrier separation: CNQDs vs GQDs

First excited state (S1)

(a) CNQDs in the of various dimensions

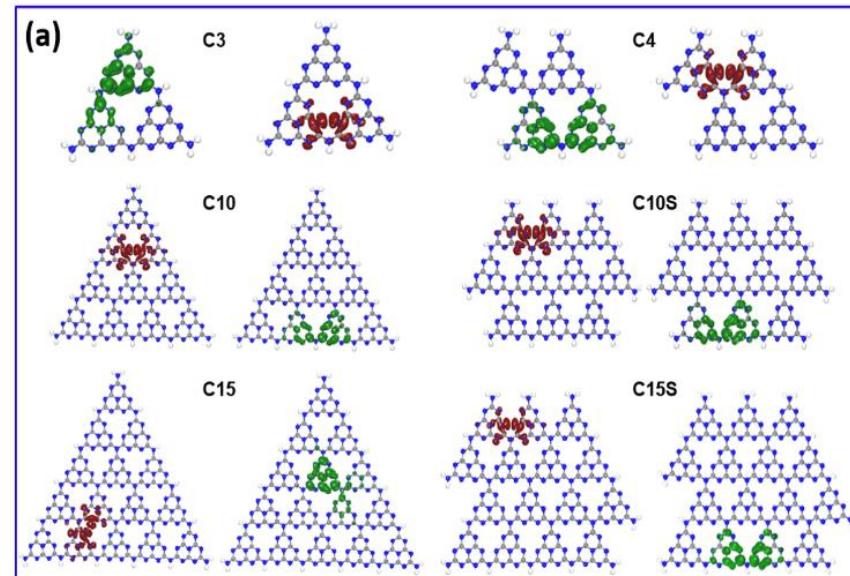
Dark brown (dark green) iso-surface color(s) indicate HOMO (LUMO) Wave functions.

(b) zigzag (ZZ), armchair (AC) and zigzag-armchair mix (MIX) edged GQDs

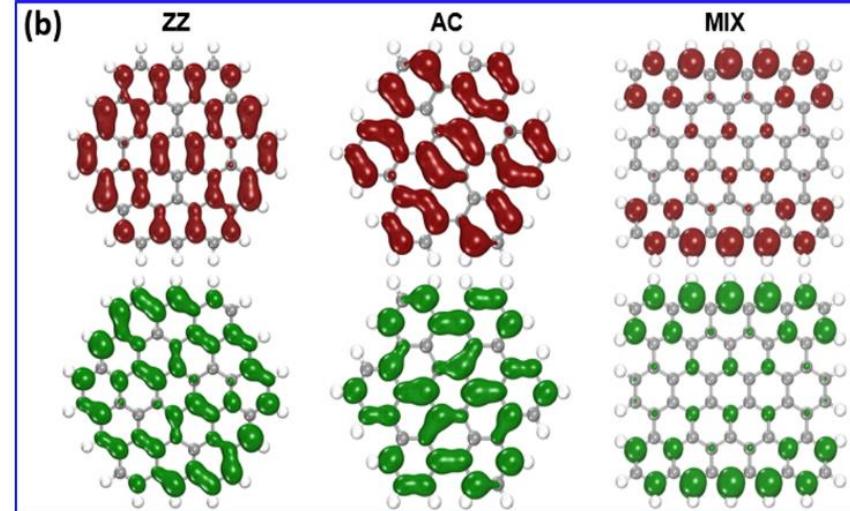


Band gap tuneability

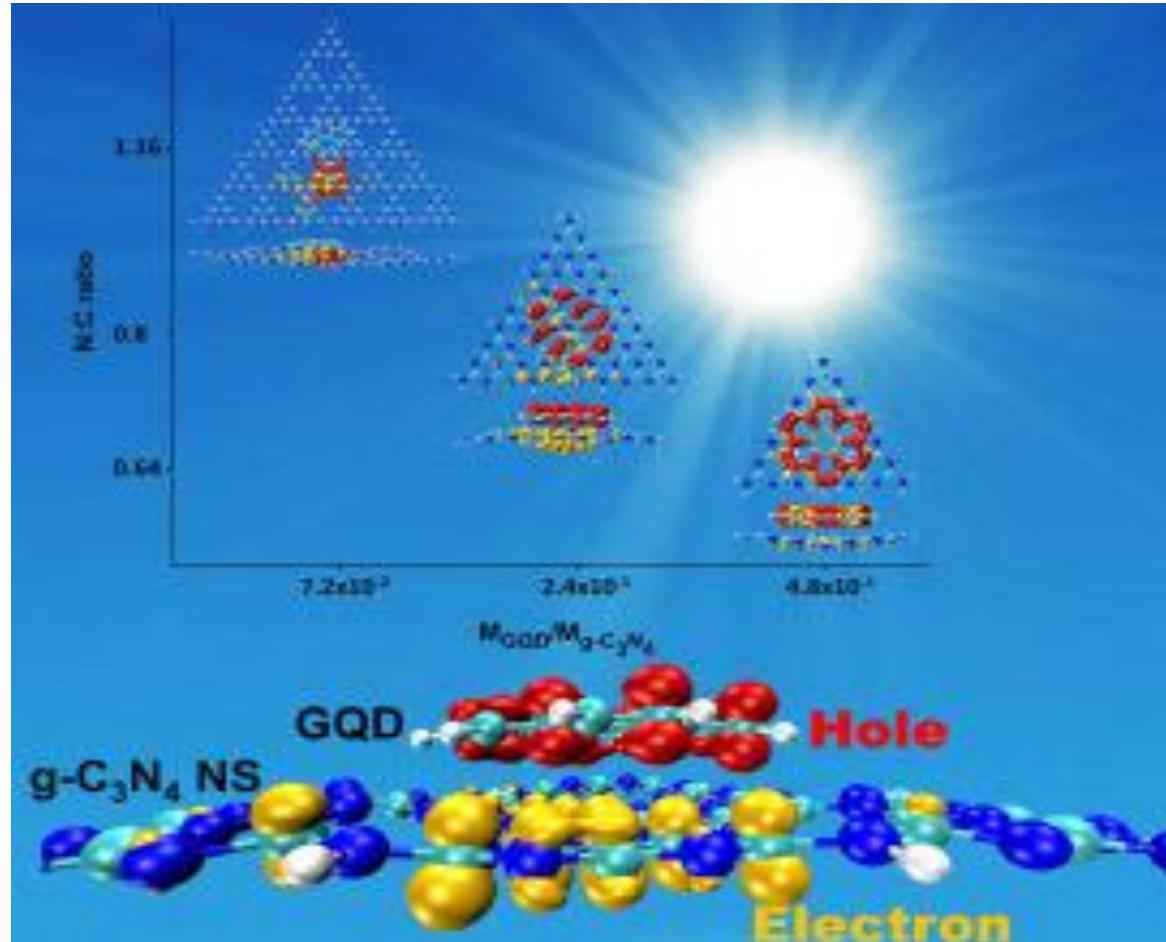
(a) CNQDs: $E_g > 2.7\text{ eV}$



(b) GQDs: $E_g \sim 1 - 2\text{ eV}$



Carbon-nanodot Sensitized Graphitic Carbon Nitride

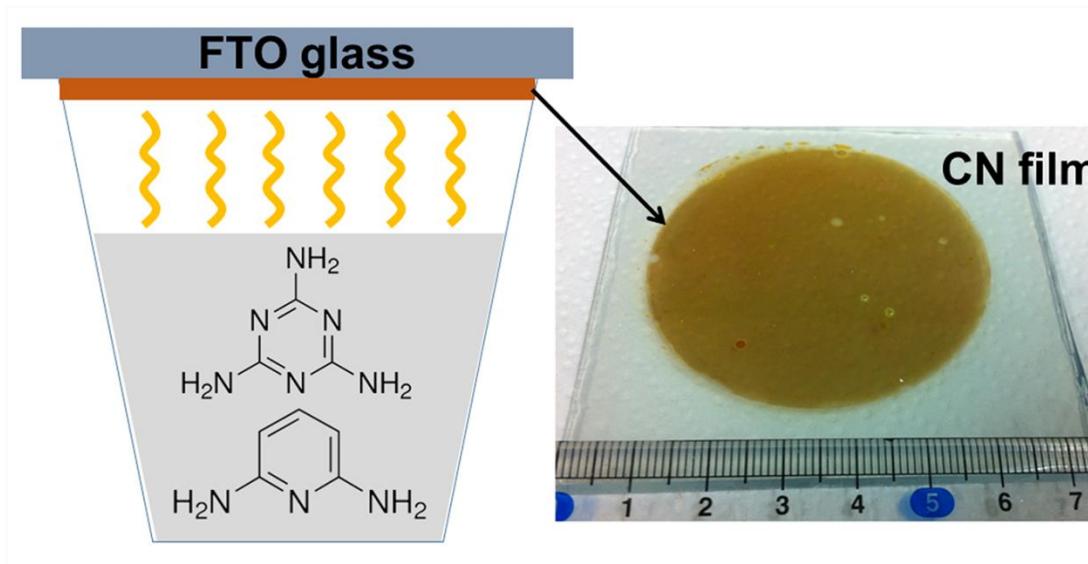


GQDs regulated charge separation:

- ✓ Nitrogen to carbon (N:C) ratio regulates the exciton charge separation, guiding the design of appropriate GQD assembly over $\text{g-C}_3\text{N}_4$ nanosheets.

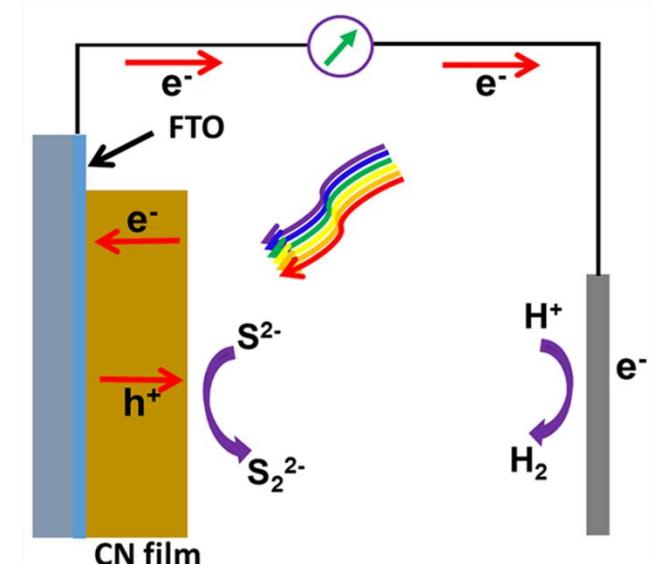
Efficiency Enhancement of Carbon Nitride Photoelectrochemical Cells via Tailored Monomers Design

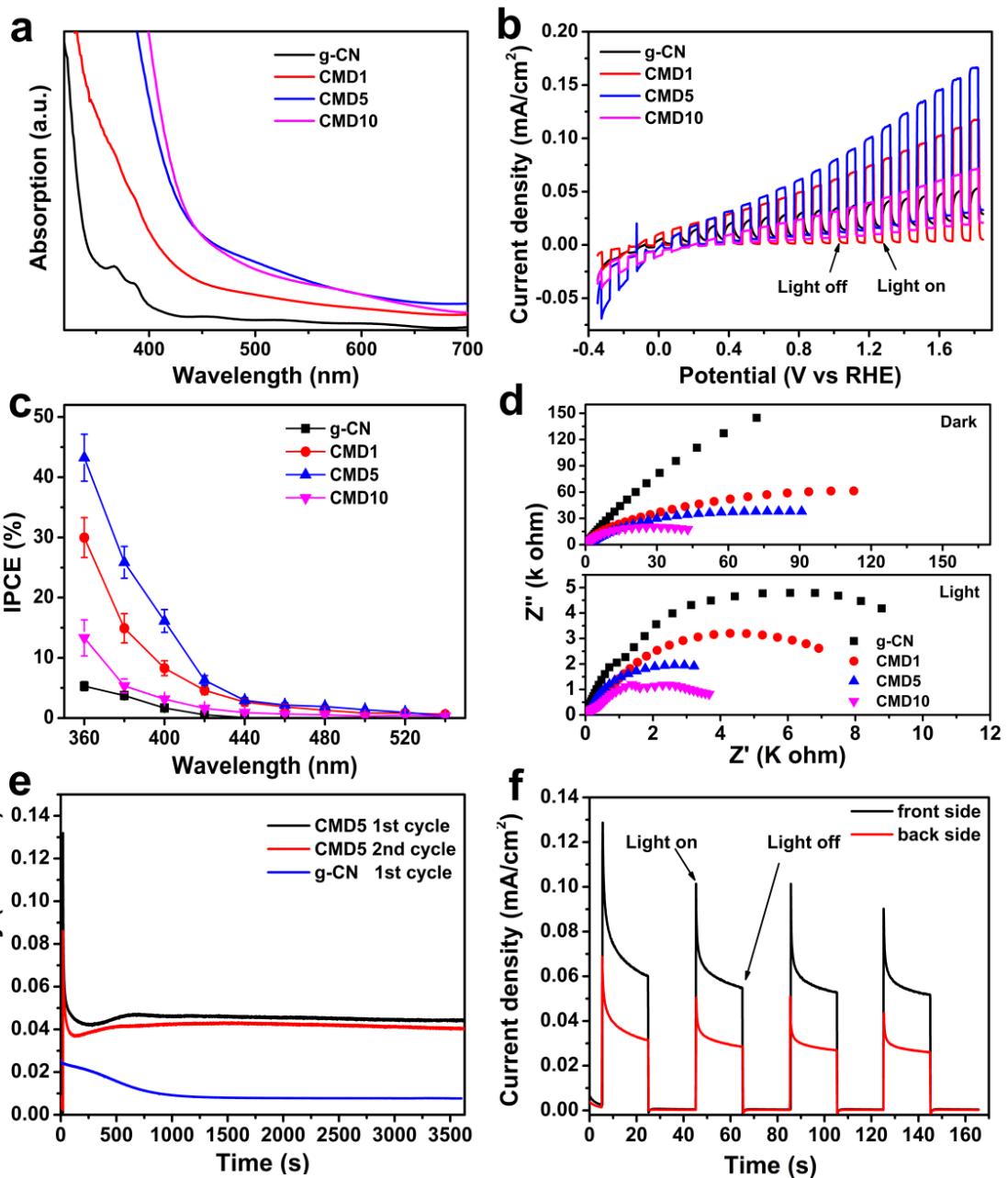
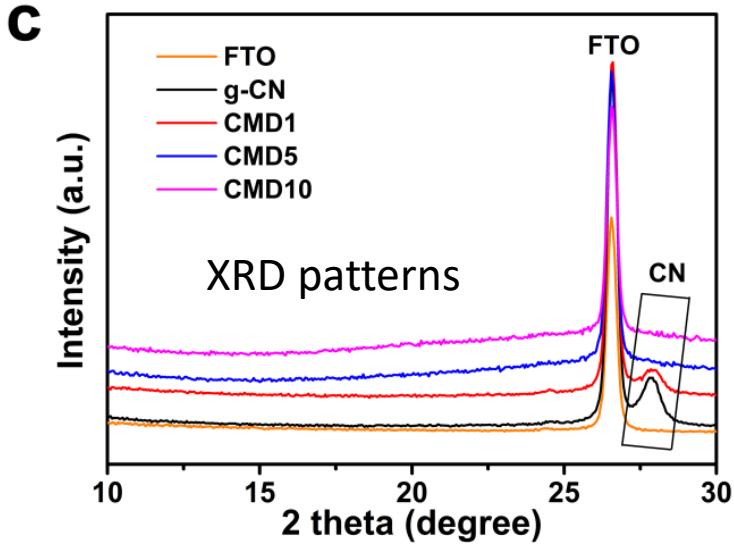
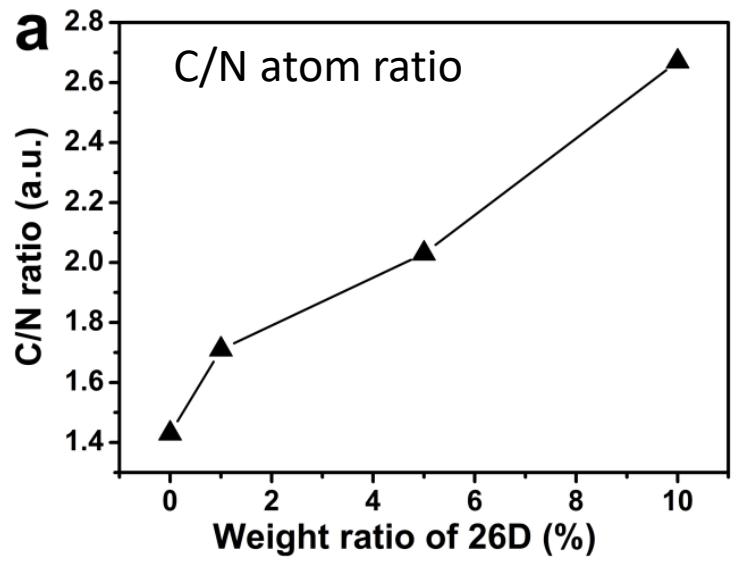
By Juncao Bian, Lifei Xi, Chao Huang, Kathrin M. Lange, Rui-Qin Zhang,* and Menny Shalom*



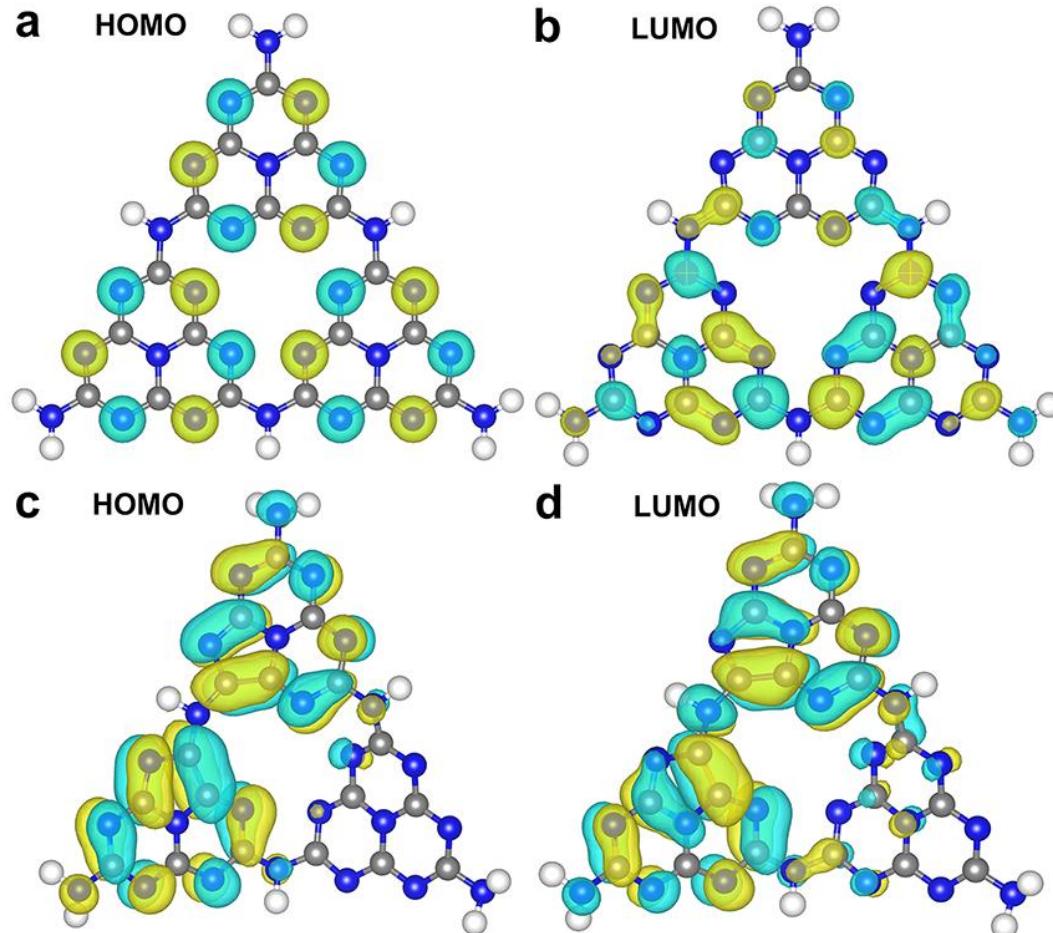
melamine

2, 6-Diaminopyridine (26D)





Improvement through C=C π bond generation by annealing

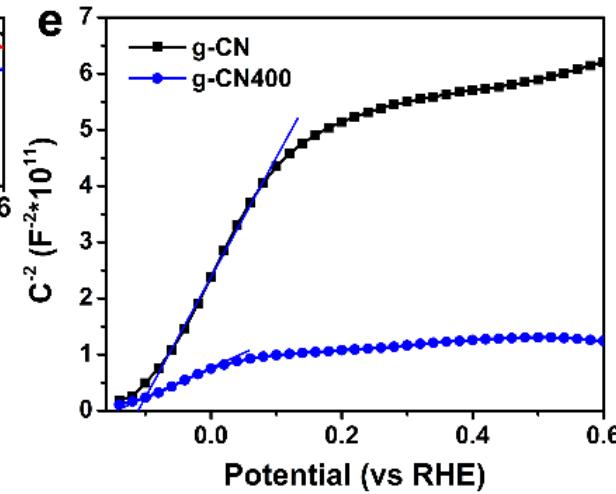
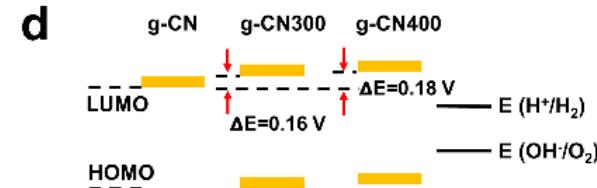
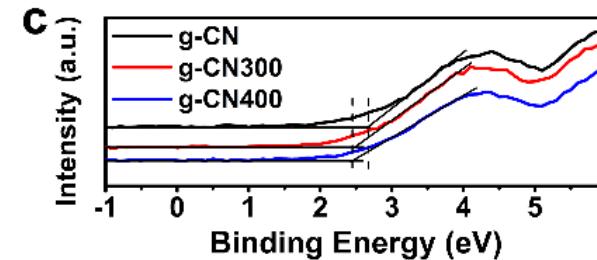
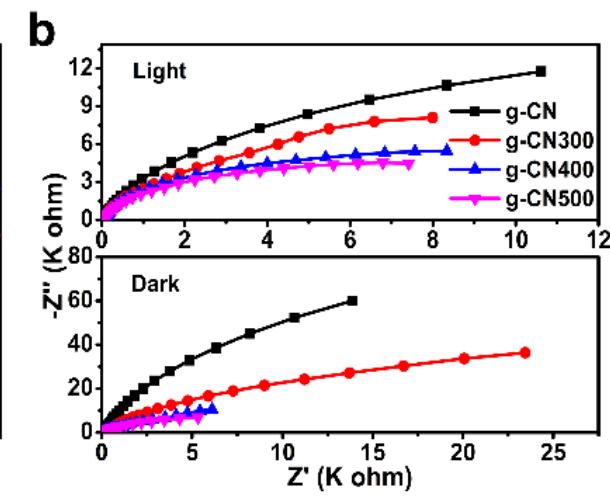
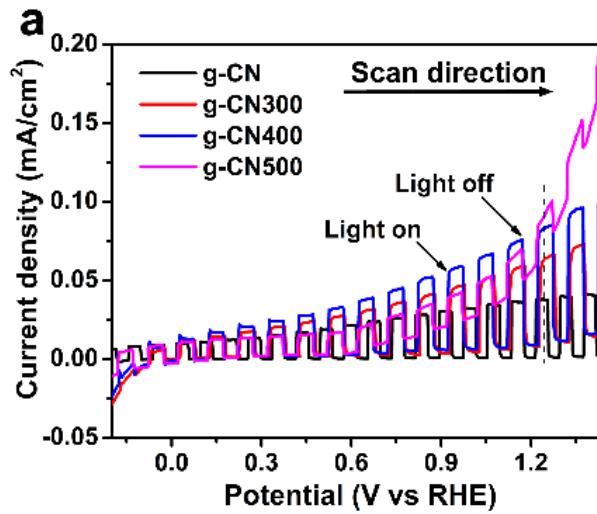
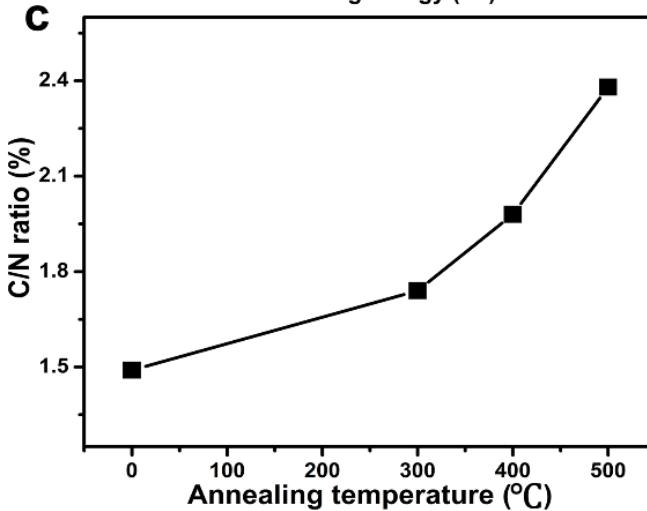
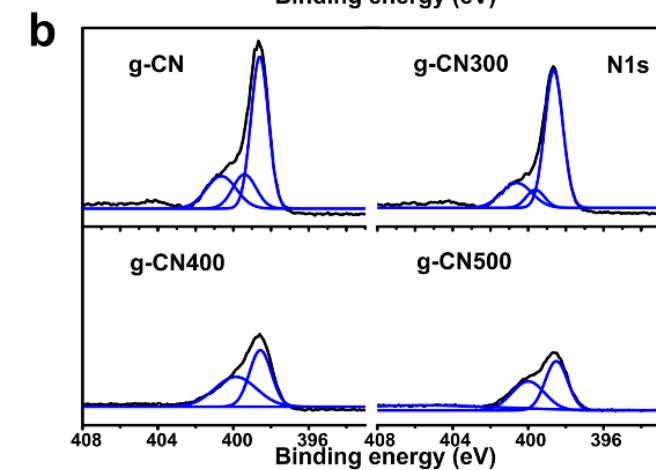


a

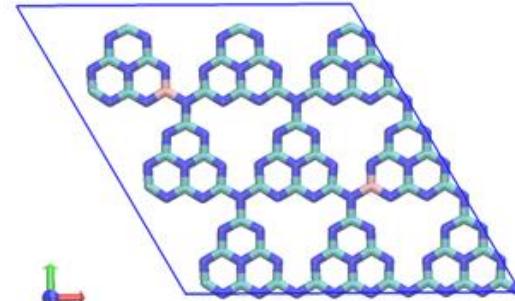
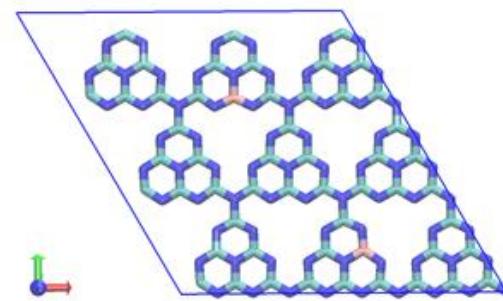
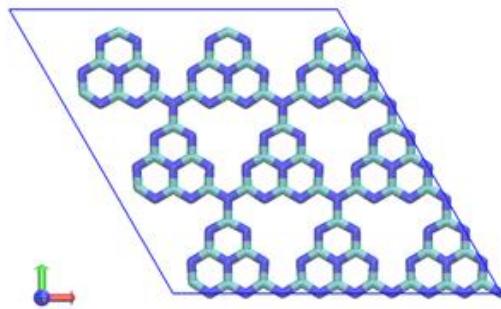
C1s

g-CN g-CN300 g-CN400 g-CN500

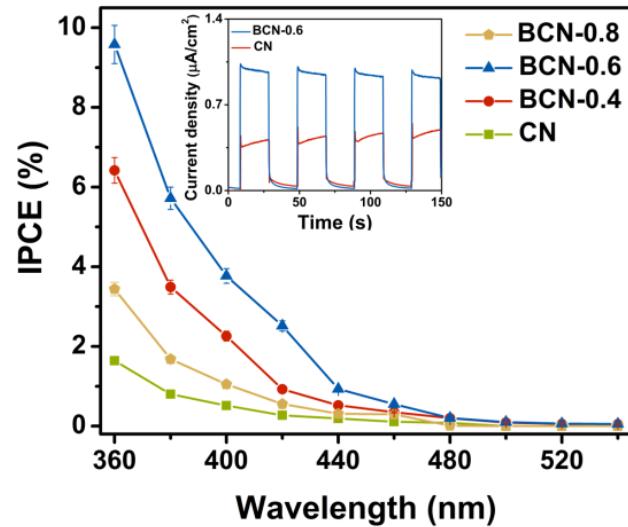
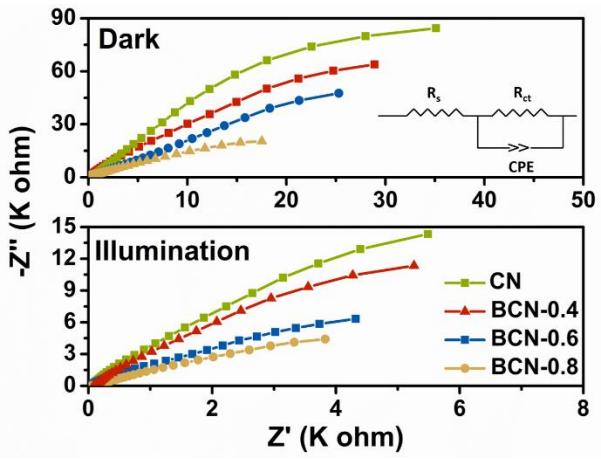
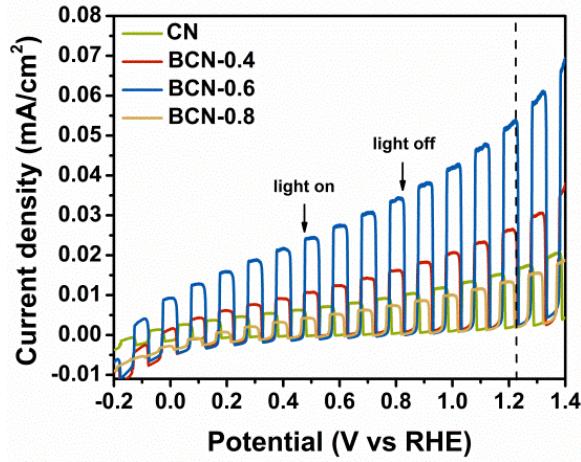
Binding energy (eV)

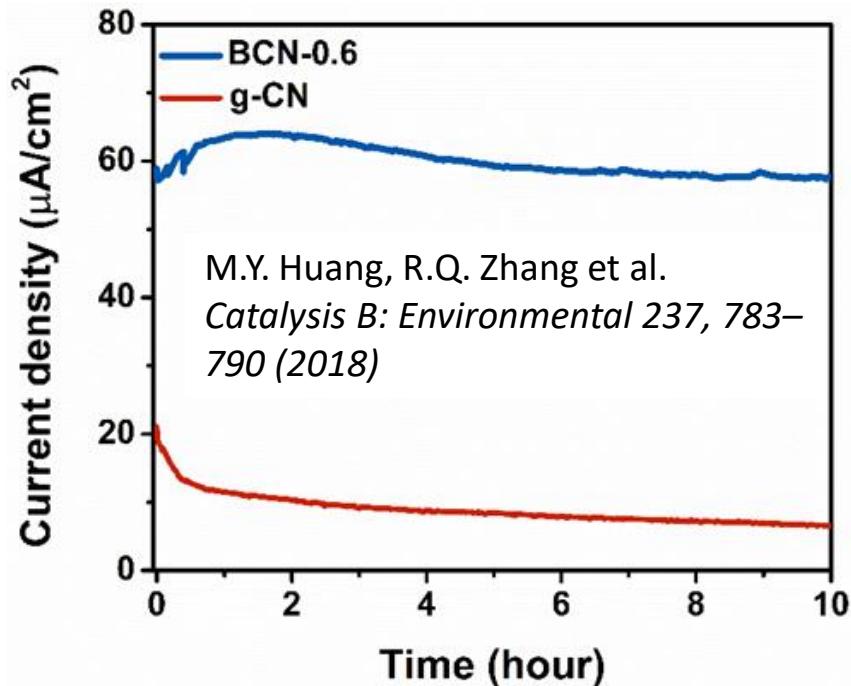
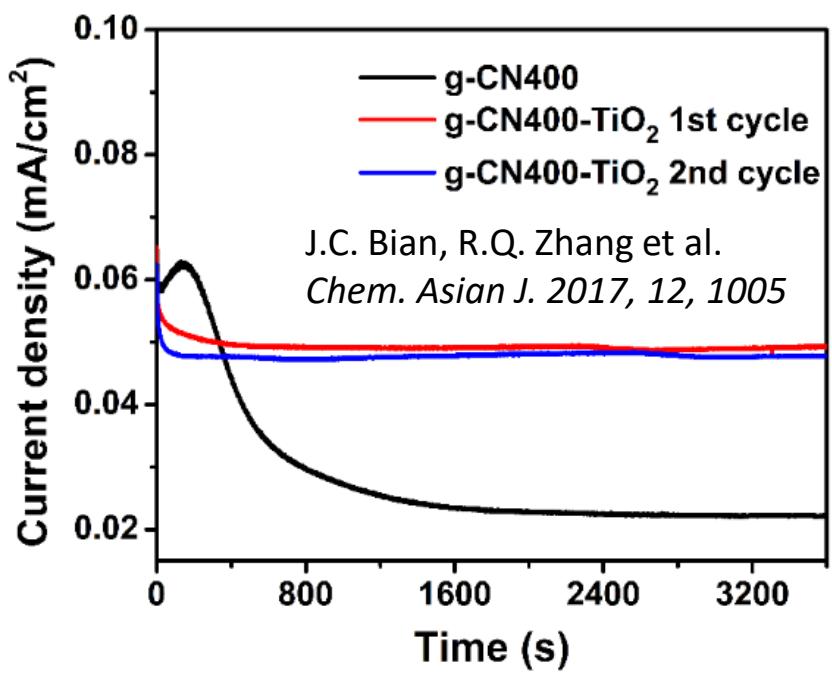
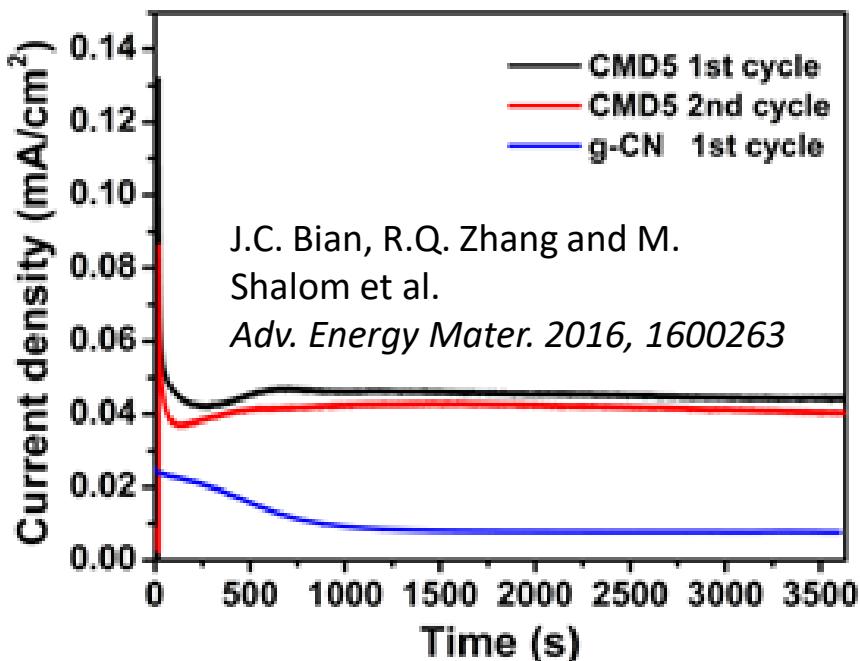
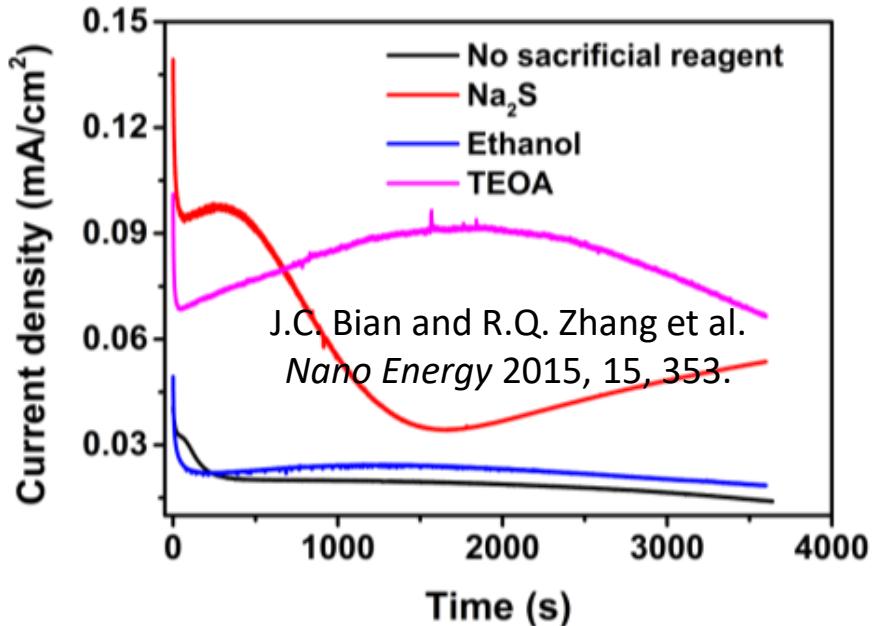


Improvement by Boron Doping



pristine CN (left) and BCN-0.6 with two C substituted by B at corner (middle) and bay (right) sites



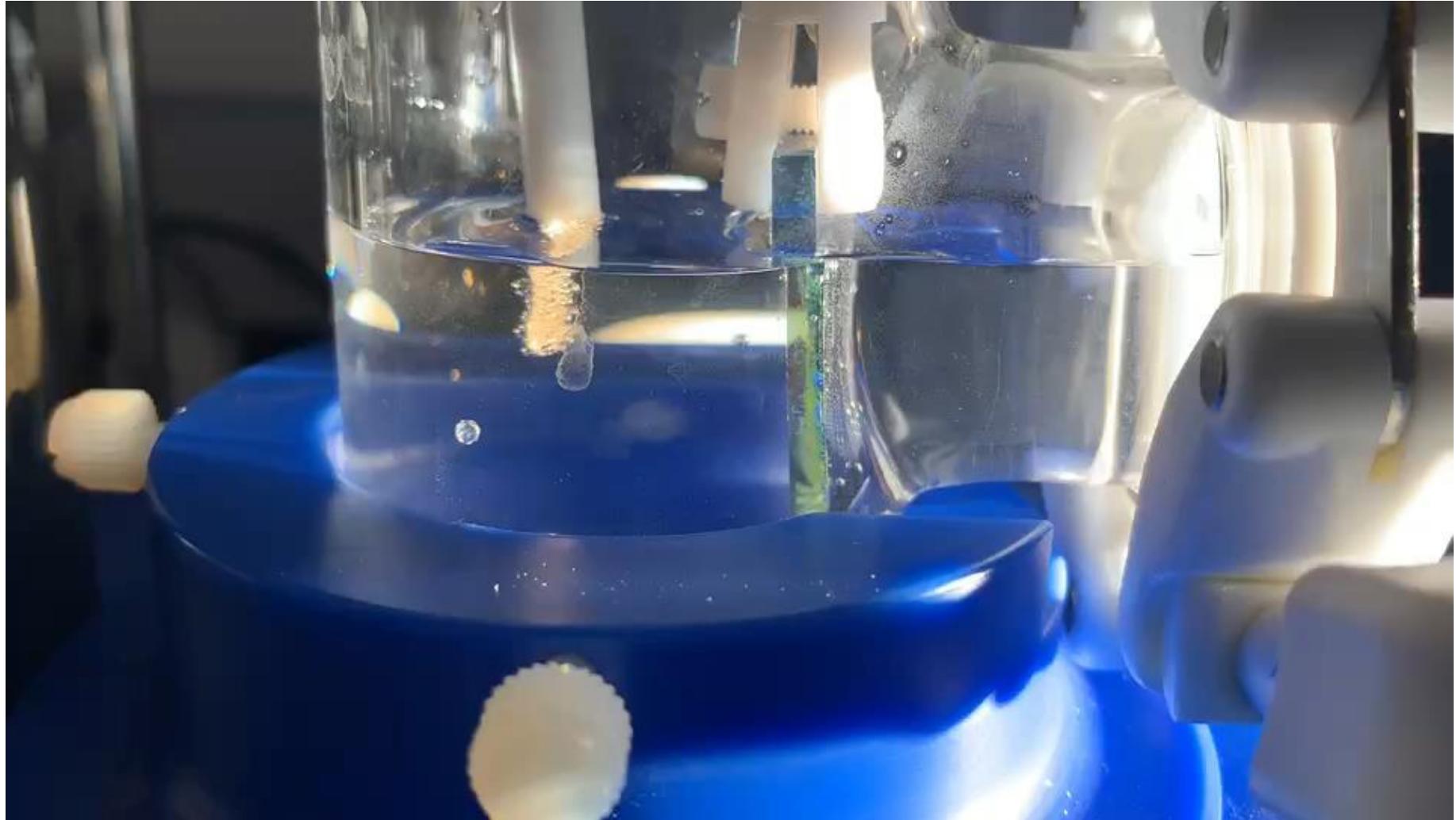


Review: Recent developments on carbon nitride based films for photoelectrochemical water splitting

W. Xiong, F. Huang, R.Q. Zhang,
Sustainable Energy & Fuels
4, 485 (2020)

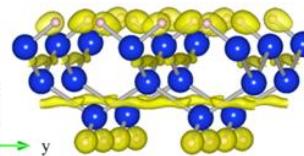


Demonstration of PEC H₂ generation



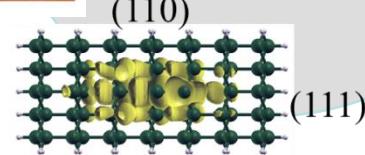
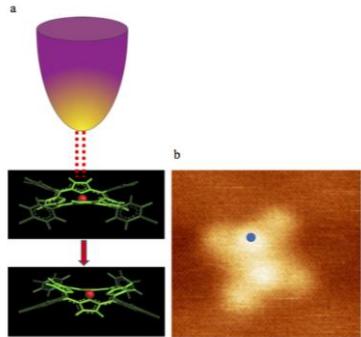
Summary

Stress/Strain
Engineering

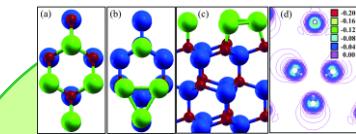


Confined
Quantum
States and
Their
Manipulation

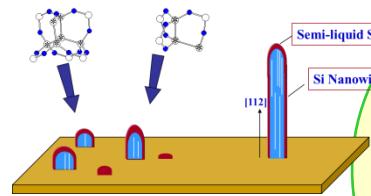
Surface
Engineering



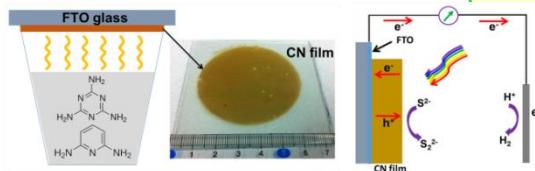
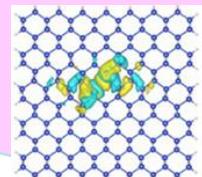
Defect
Engineering



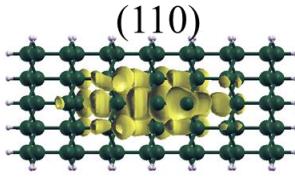
Confined
Catalysis
and Growth



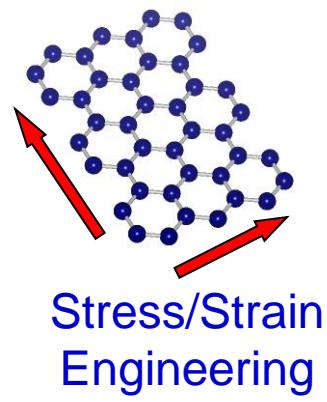
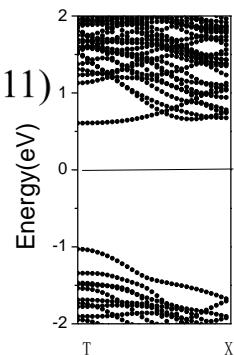
Excited State
Manipulation



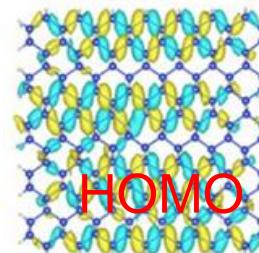
Thank You!



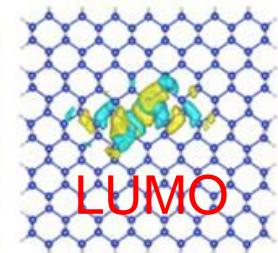
Surface
Engineering



Stress/Strain
Engineering



HOMO



LUMO

Excited State Engineering