

Nanowires for Low Power Consumption Gas Sensors



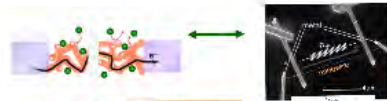
J. Daniel Prades
dprades@el.ub.es



viii intl. workshop in semiconductor gas sensors
sept. 2012 krakow



Nanowire



Identical nanowires!

$$R_s = \lambda \cdot R_i$$

$$S = \frac{\lambda R_i}{R_s} \frac{\partial R_s}{R_i}$$

Nature Mater 10, 2999 (2011)

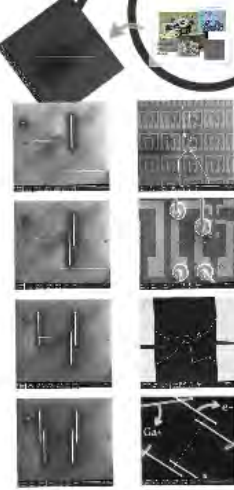
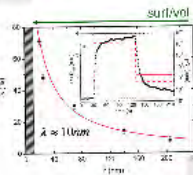
ONE single nanowire encodes **ALL** the sensing information!



self-heating



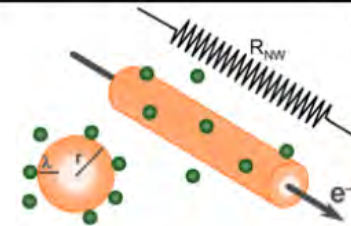
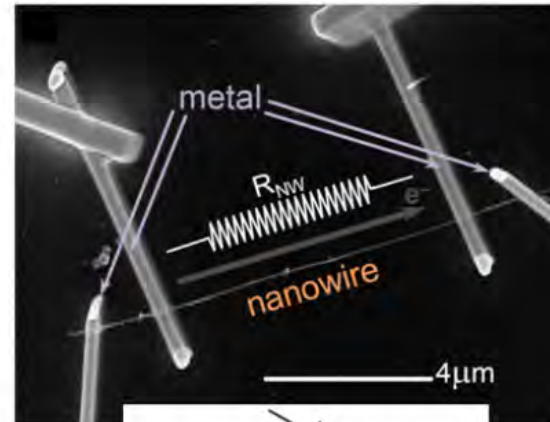
x1,000,000



picoAmps



Nanotechnology 18, 095511 (2007)
Materials 3-08, 6 (2011)



$$R_T = \lambda \cdot R_i$$

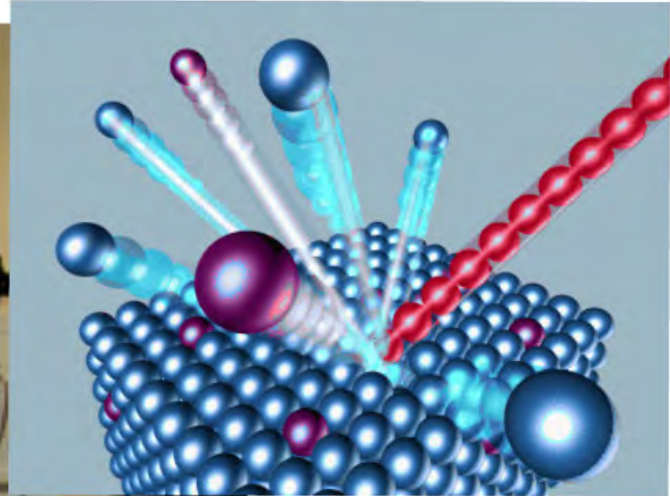
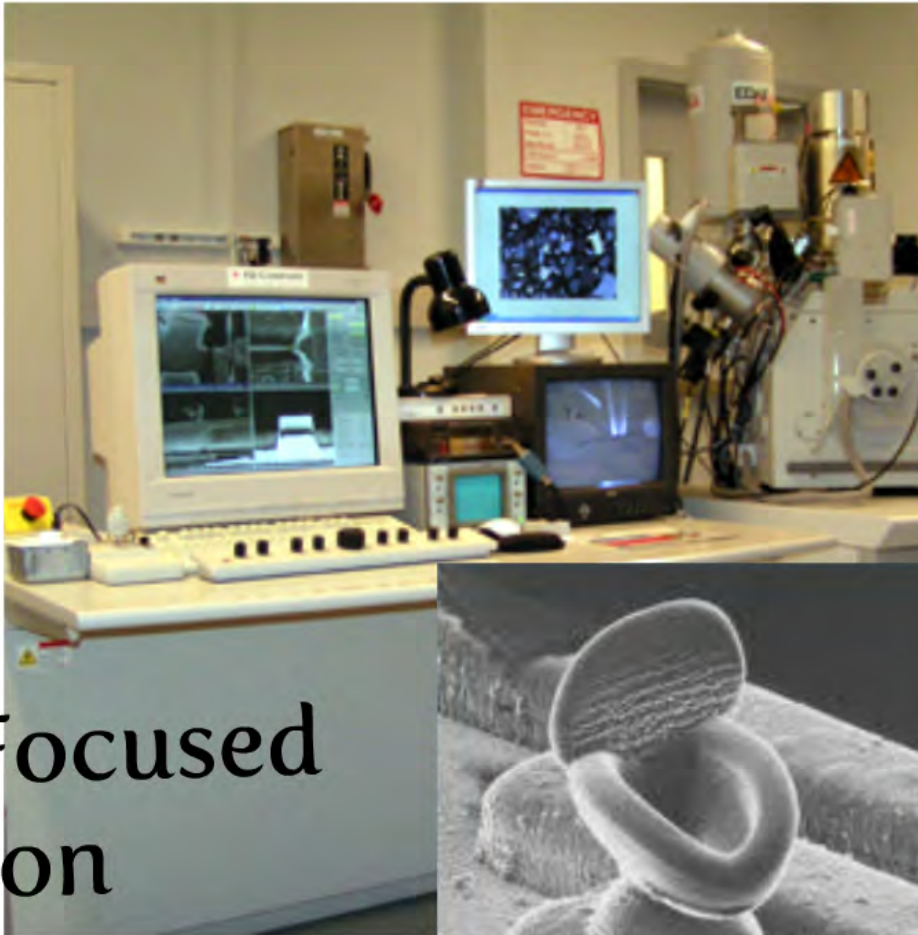
(identical nanowires)

$$S = \frac{\Delta R_T}{R_T} = \frac{\delta R_i}{R_i}$$

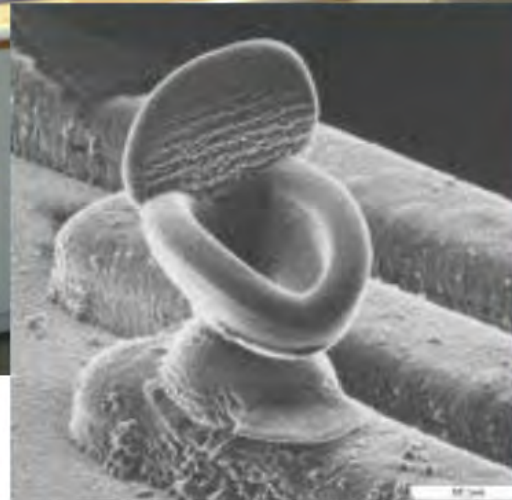
Adv. Funct. Mater. 18, 2990 (2008)

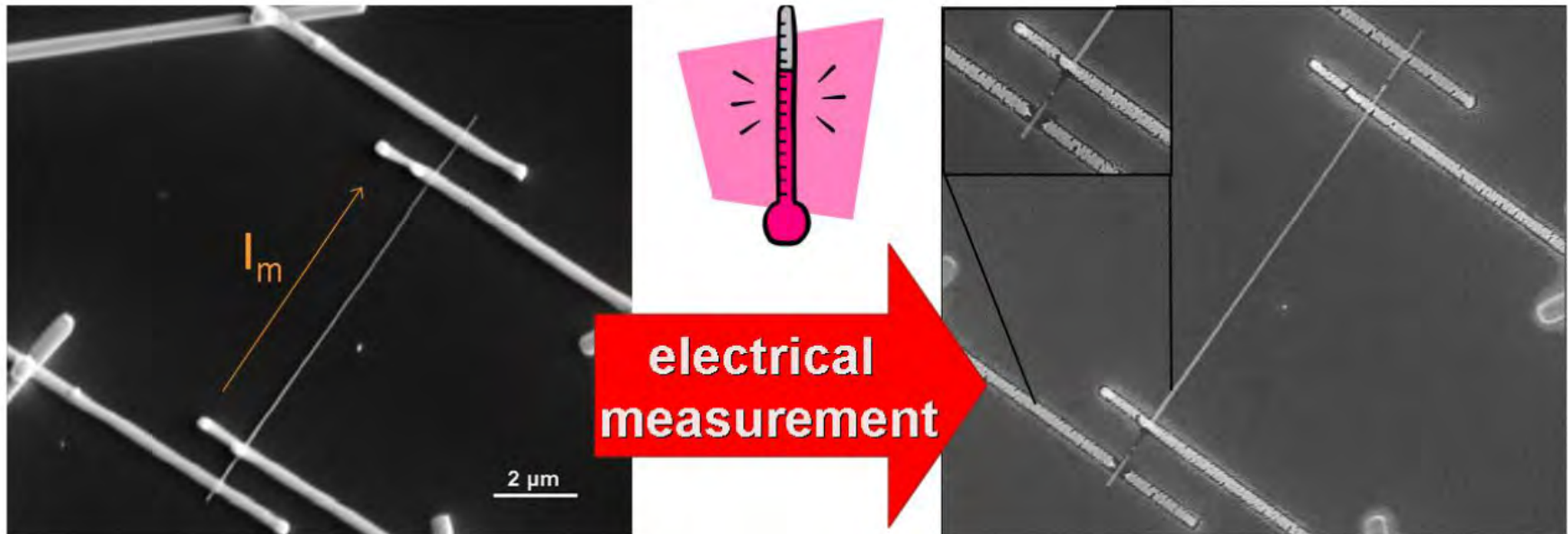
ONE single nanowire encodes ALL the sensing information!

Nanotechnol. 17, 5577 (2006)

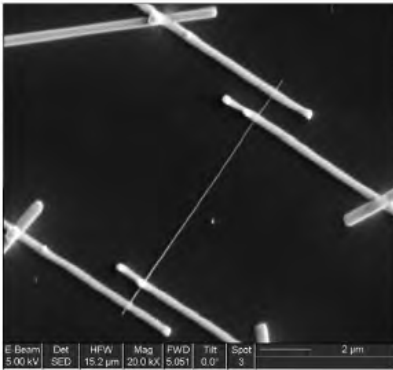


Focused Ion Beam

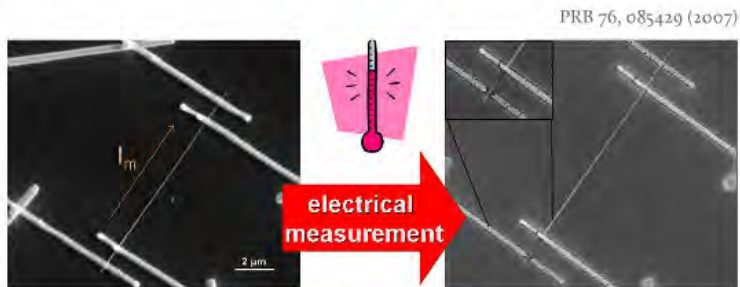




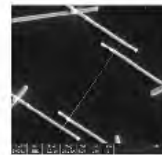
self-heating



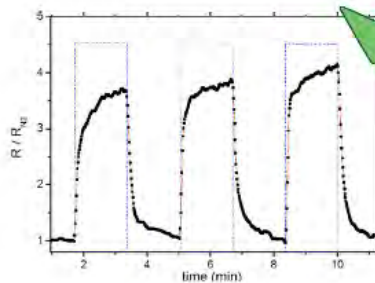
×1,000,000



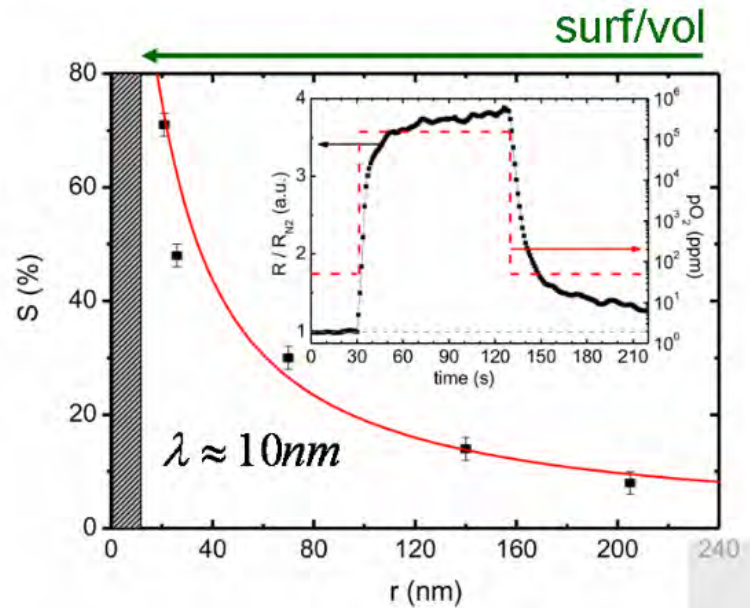
self-heating



×1,000,000

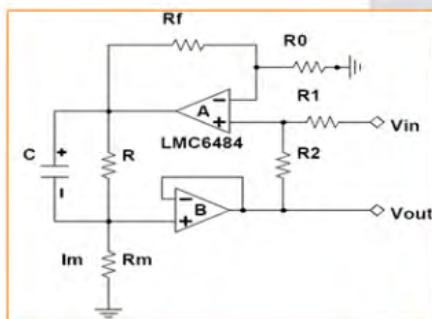


- Adv Funct Mater 18, 2990 (2008)
- J Phys Chem C 112, 14639 (2008)
- PCCP 11, 7105 (2009)
- PCCP 11, 10881 (2009)
- Sens Actuators B 140, 337 (2009)
- PCCP 12, 2401 (2010)
- Nanoscale 3, 630 (2011)





picoAmps



Nanotechnology **18**, 495501 (2007)
mst/news **3/08**, 6 (2008)

Self-heating



why? (nano)integrated heat source

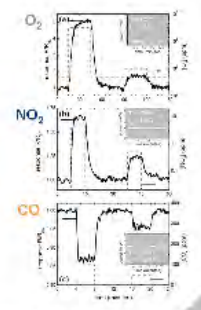
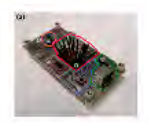
Carbon nanotube

10mW → 10uW

1000x

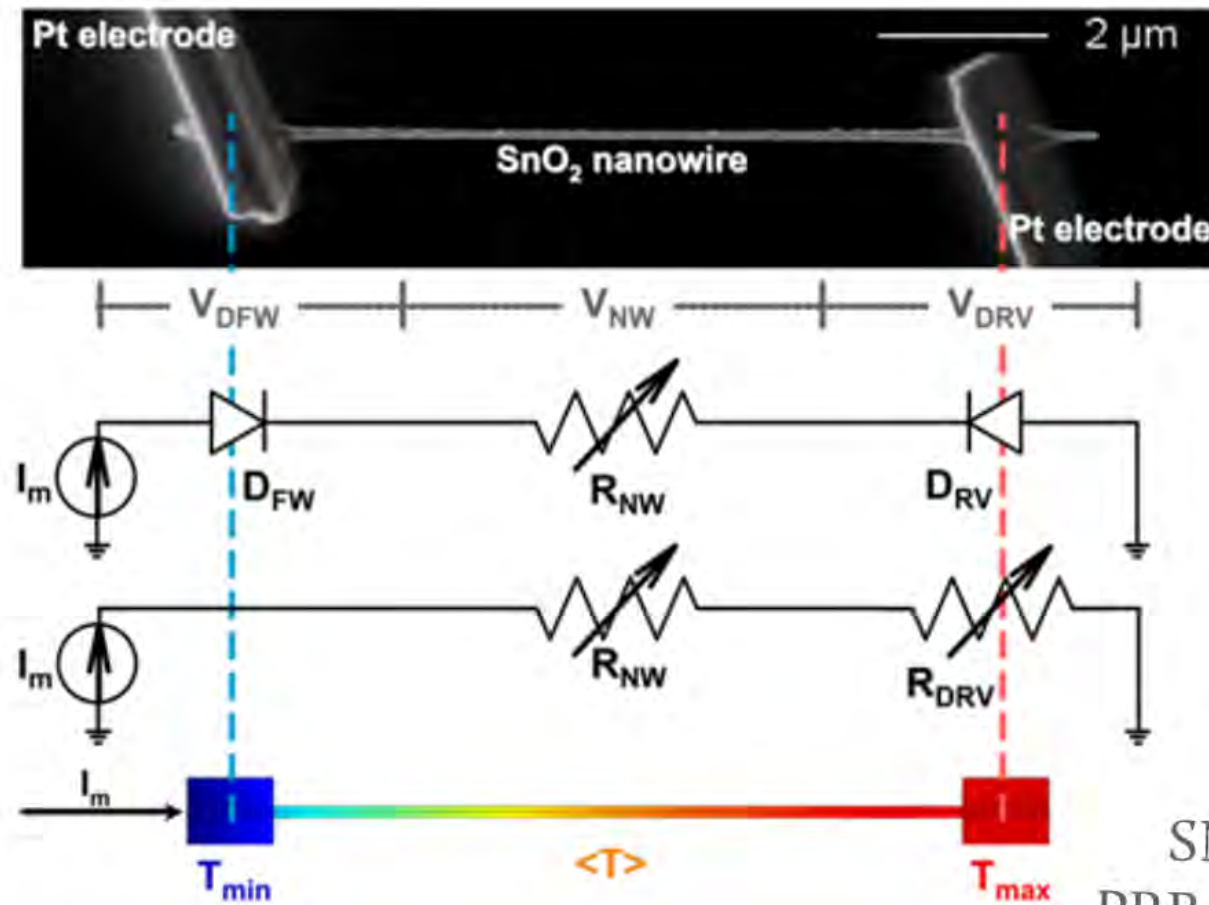
1000x

+ self-heating
energy harvesting
autonomous gas sensor

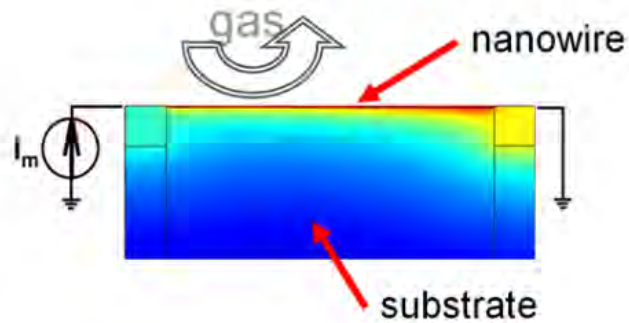


Sens. Actuators B 144, 1 (2010)

controlled self-heating?



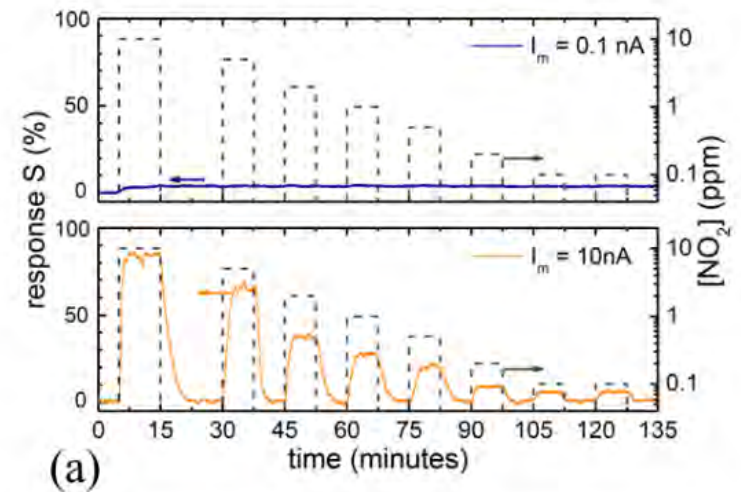
SNB 118, 198 (2006)
PRB 76, 085429 (2007)



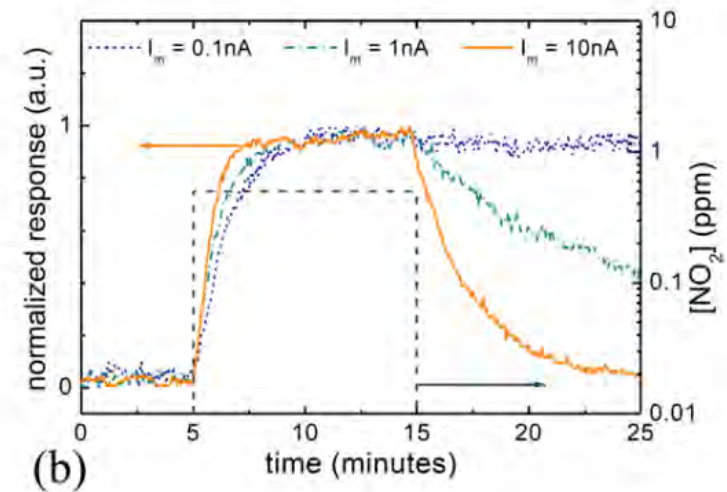
Kolmakov et al.
Nanotechnol 19,
355502 (2008)

Prades et al.
ApplPhysLett 93,
I23110 (2008)

- At very low probing current (I_m)
 - ... poor response
 - ... no recovery
- At higher probing current
 - ... better response
 - ... faster recovery



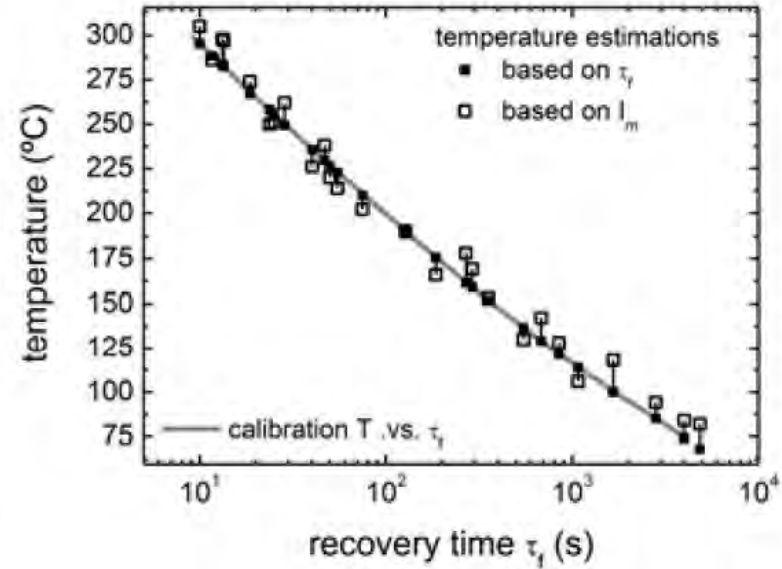
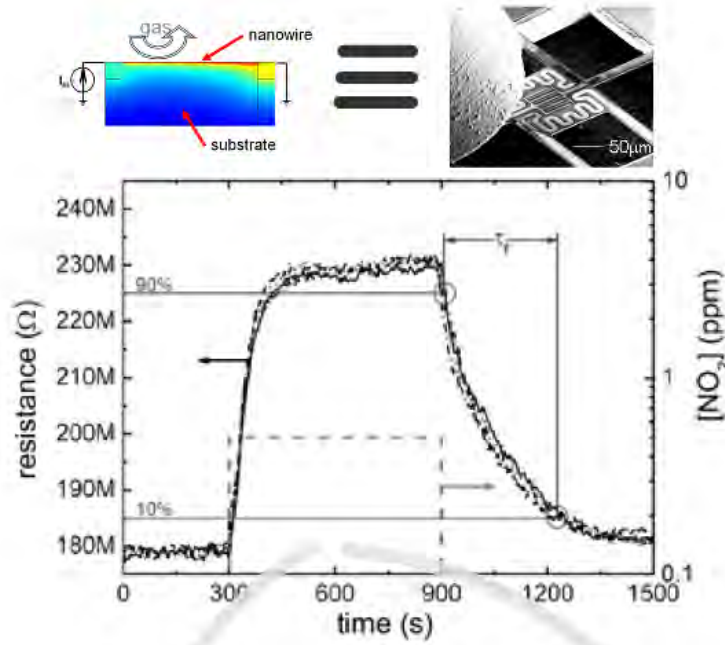
(a)



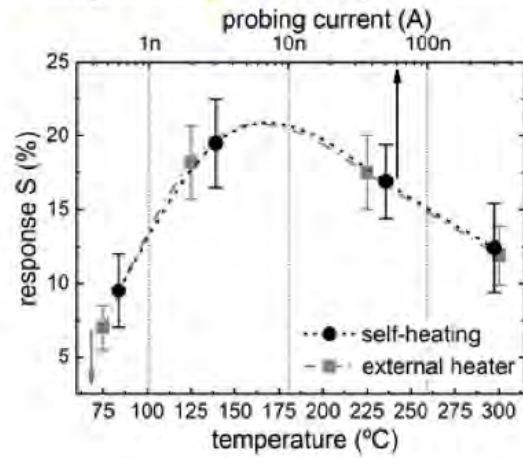
(b)

Similar to the effect of an external heater

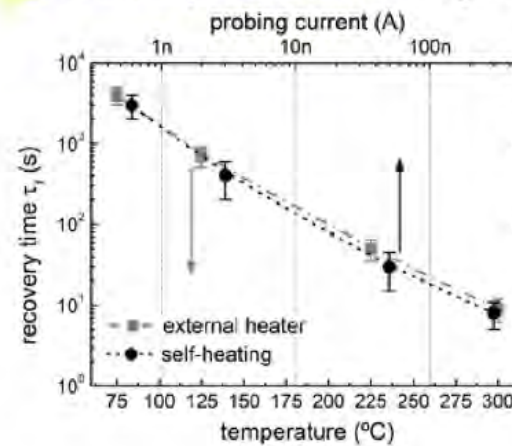
It works! :-)



response vs. temperature



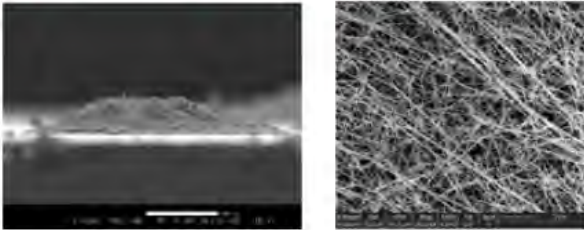
recovery time vs. temperature



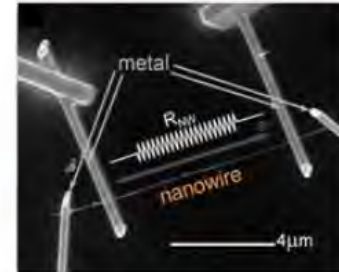
indirect
temperature
calibration
method at the
nanoscale

why? (nano)integrated heat source

1) Sensing element



porous layers, bunch of (nano)particles, ...

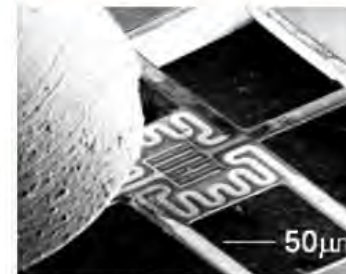


individual nanowire

2) Heating element



millimeters scale

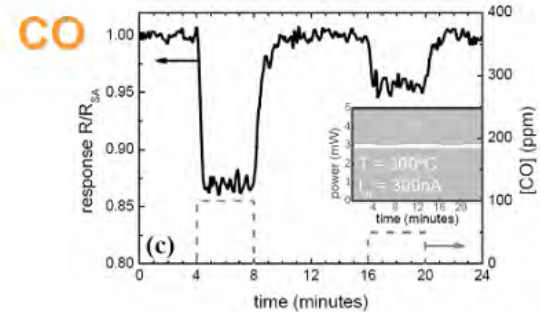
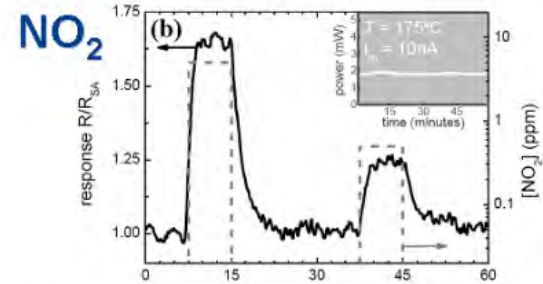
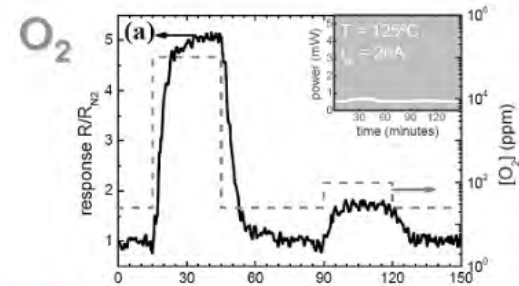
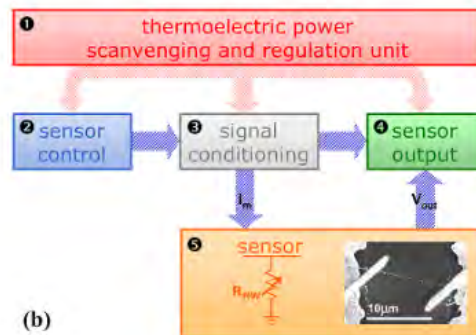
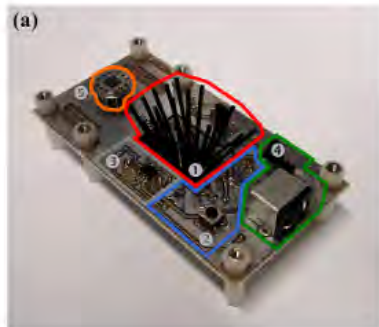


microelectronics

$$10\text{mW} \xrightarrow{\div 1000!} 10\text{uW}$$

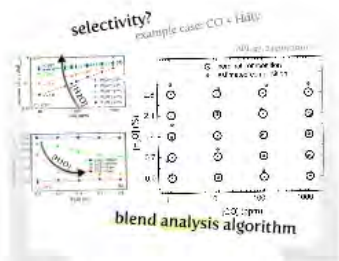
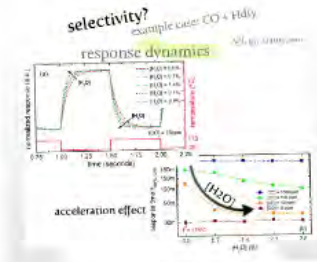
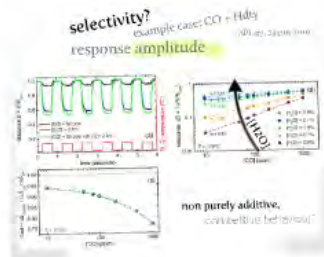
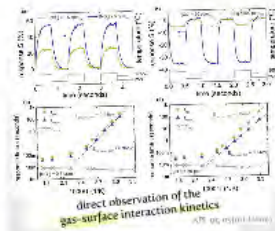
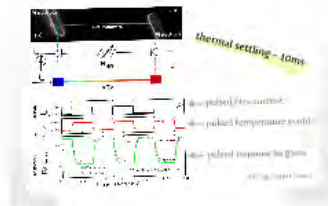
APL 93, 123110 (2008)

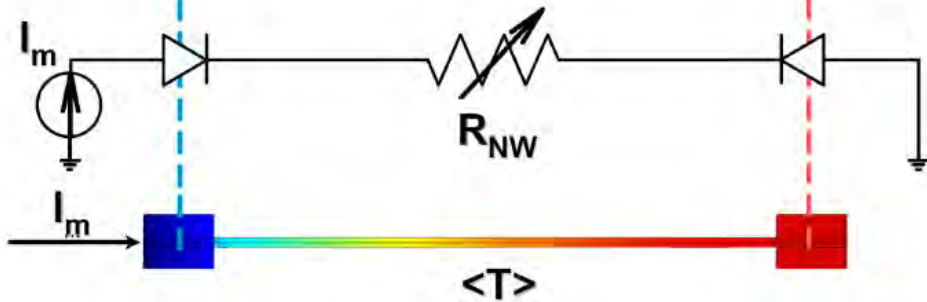
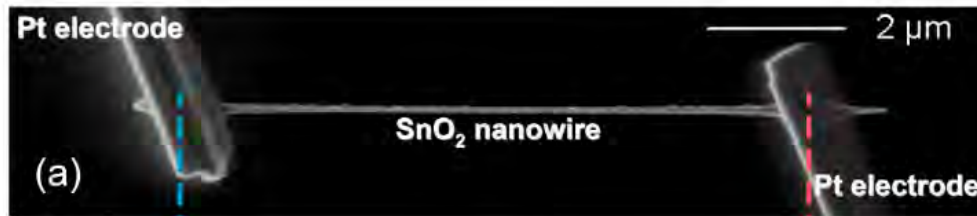
+ self-heating energy harvesting autonomous gas sensor



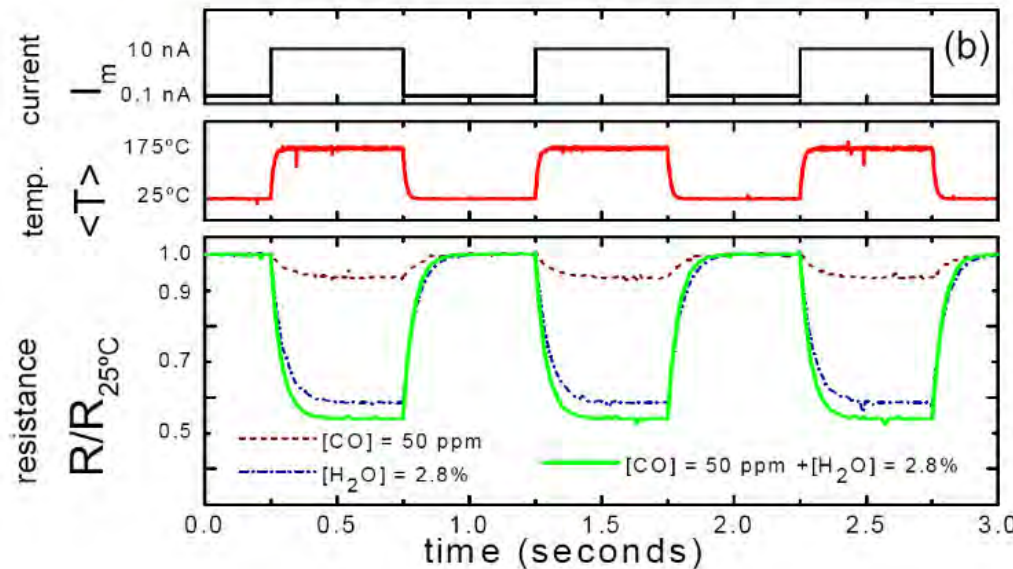
Sens. Actuators B 144, I (2010)

PULSES





thermal settling ~ 10ms

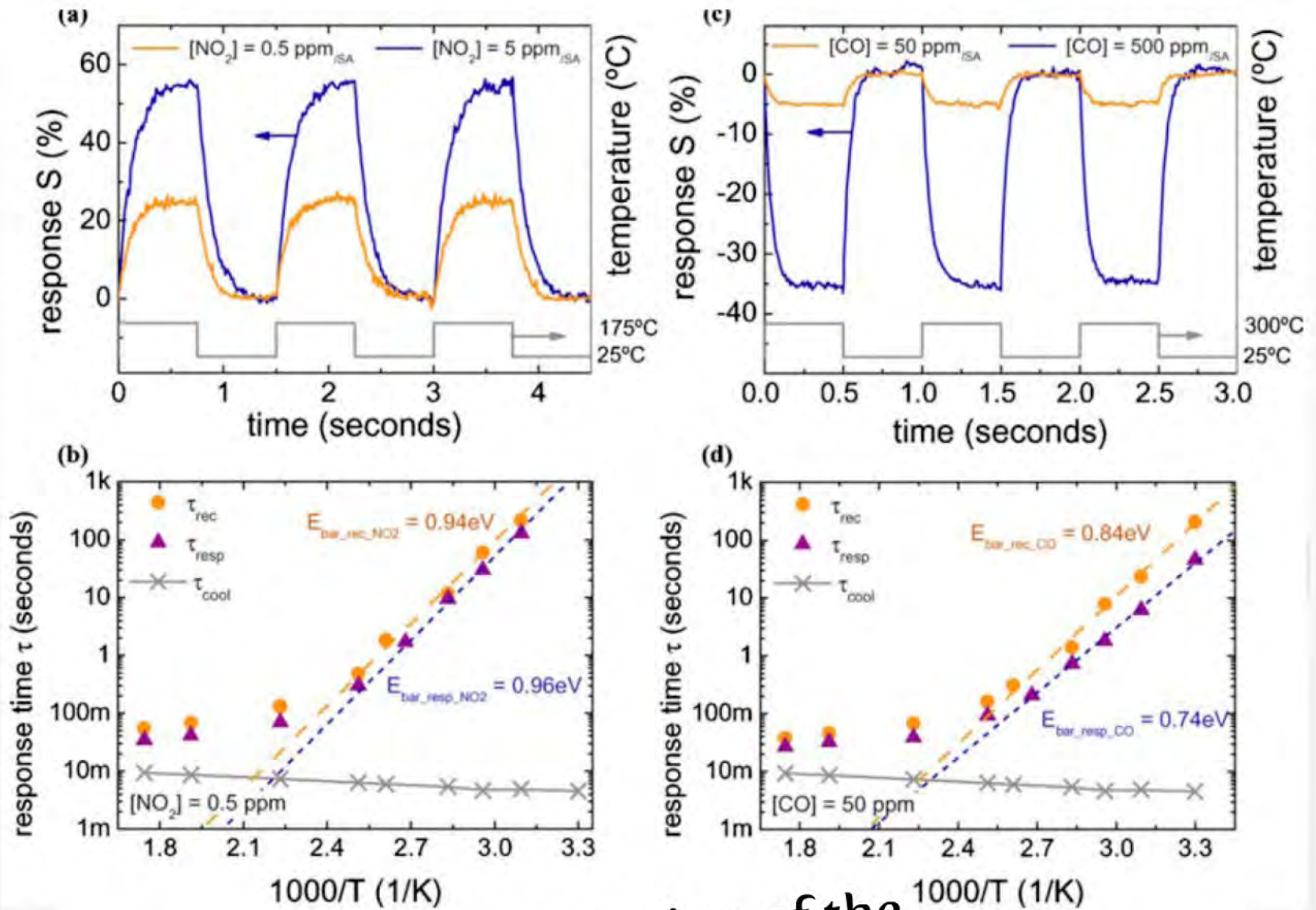


← pulsed bias current

← pulsed temperature profile

← pulsed response to gases

APL 95, 053101 (2009)



direct observation of the
 gas-surface interaction kinetics

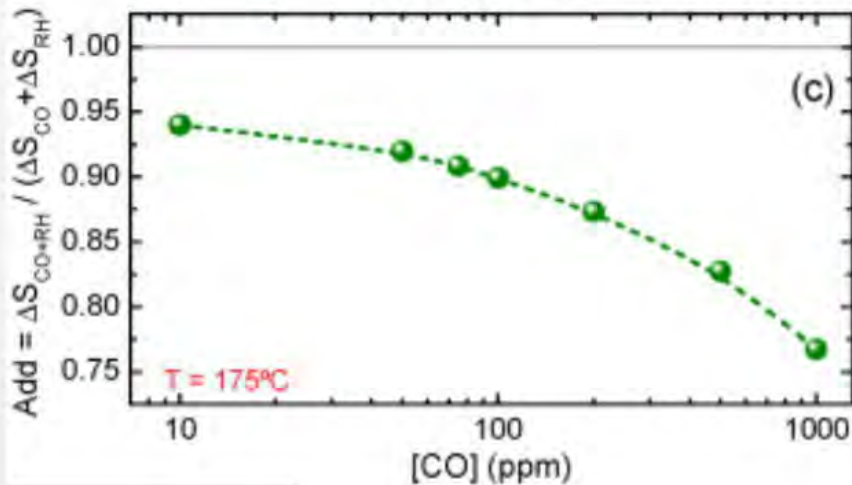
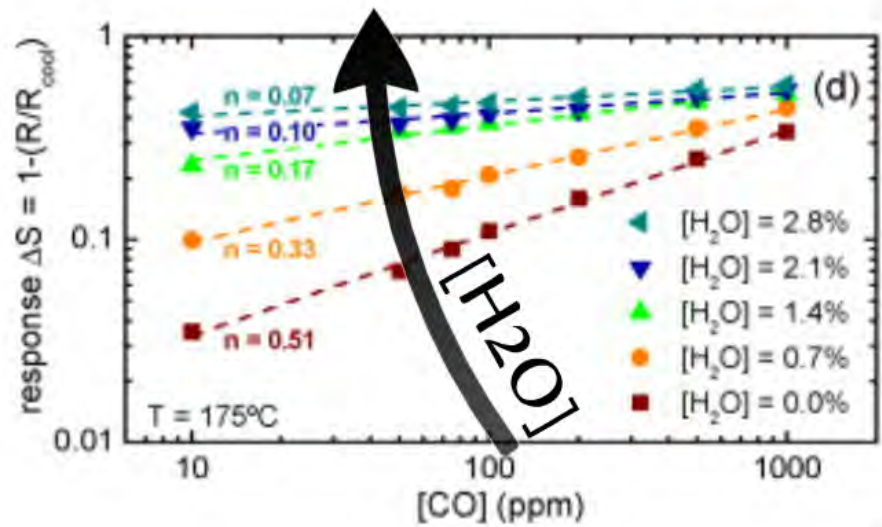
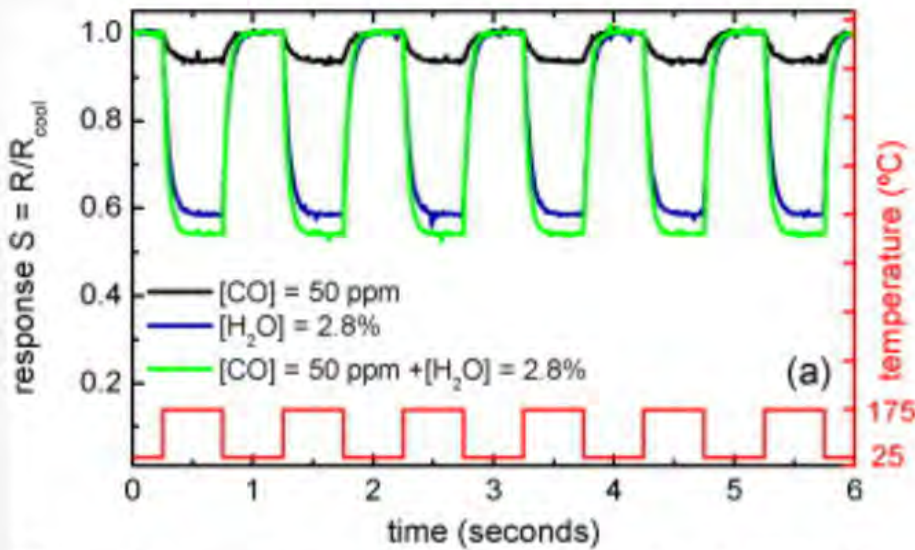
APL 95, 053101 (2009)

selectivity?

example case: CO + Hdty

APL 97, 243105 2010

response amplitude



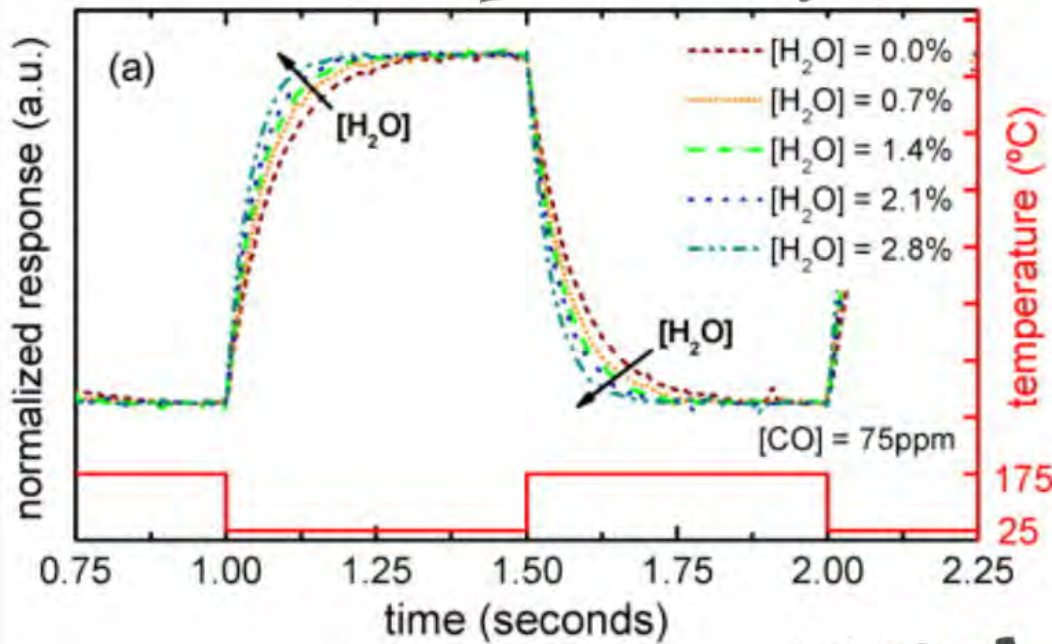
non purely additive,
competitive behaviour?

selectivity?

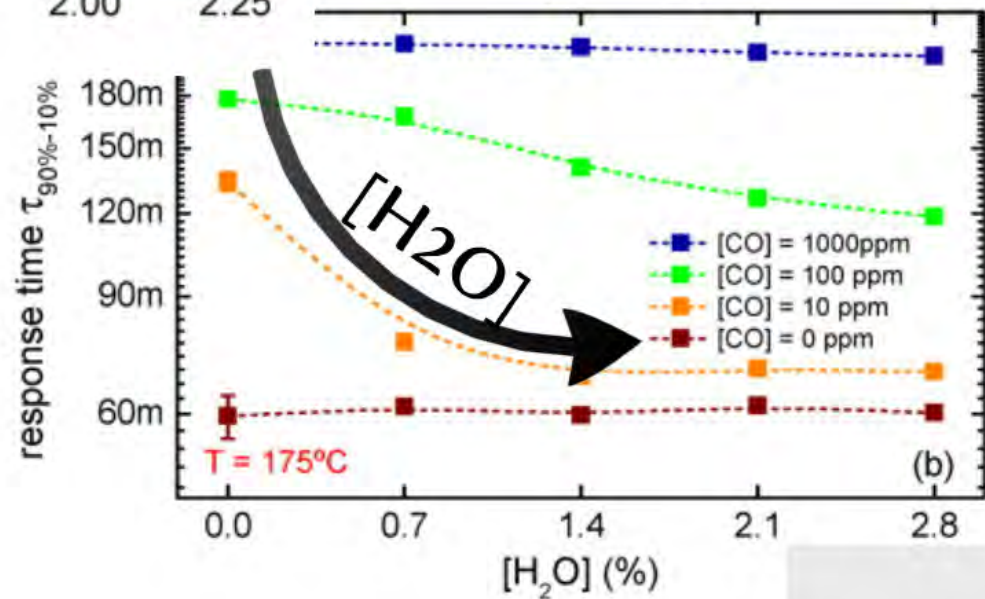
example case: CO + Hdty

APL 97, 243105 2010

response dynamics



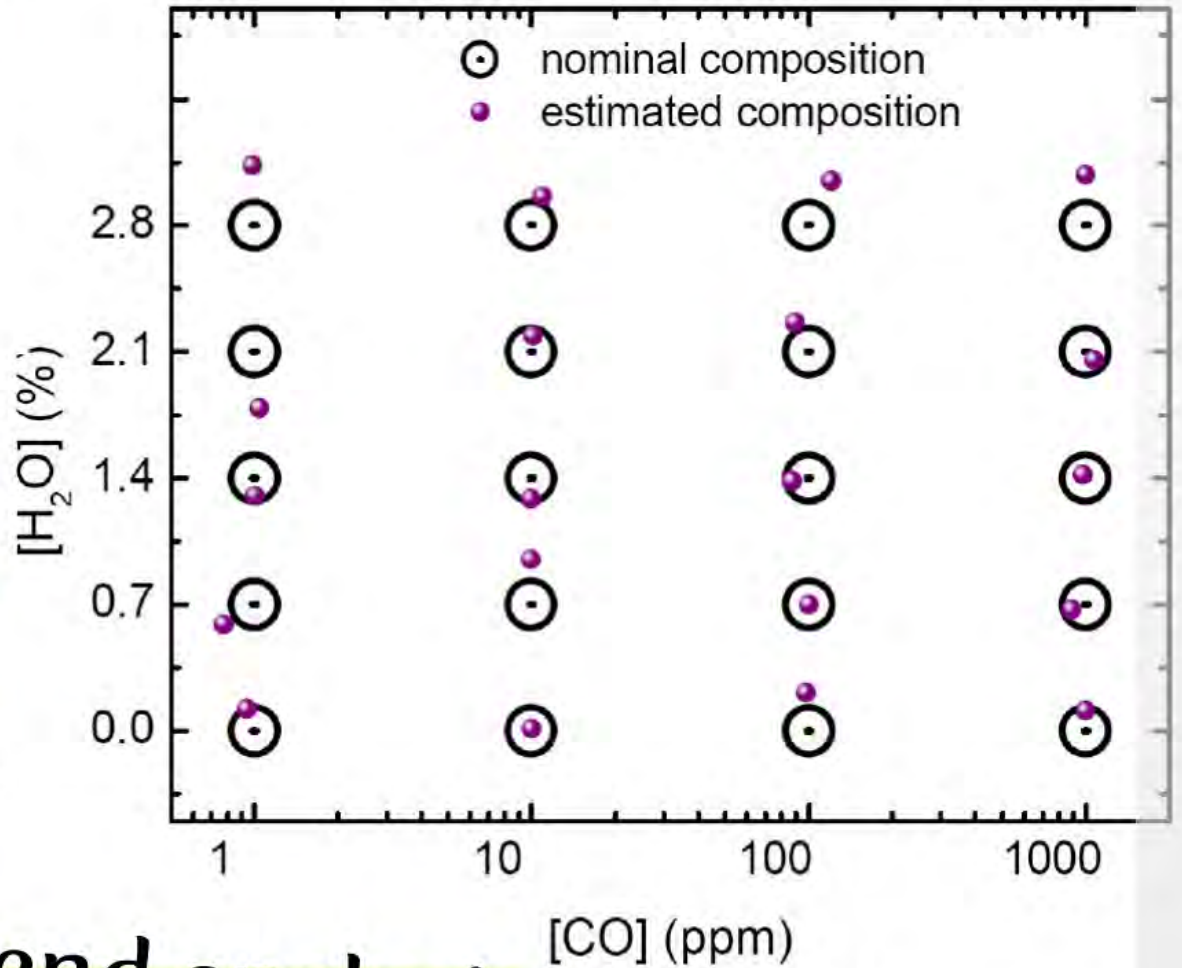
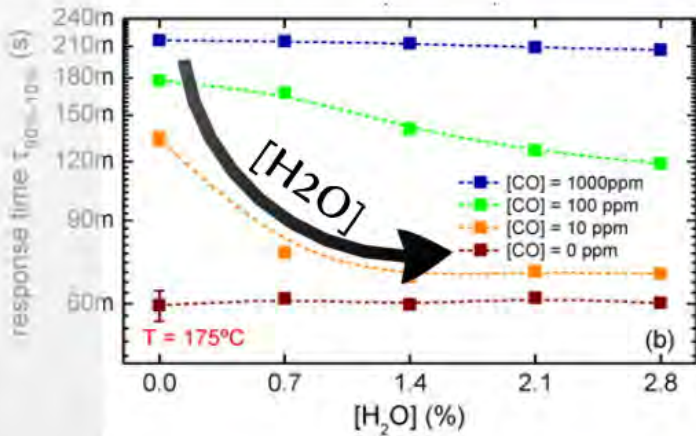
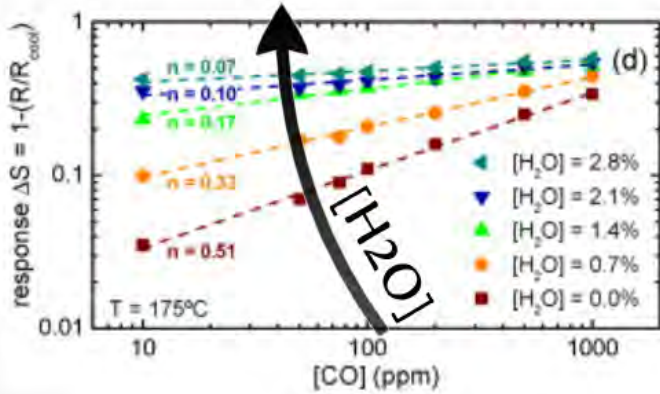
acceleration effect



selectivity?

example case: CO + H₂O

APL 97, 243105 2010



blend analysis algorithm

Nanowires for Low Power Consumption Gas Sensors



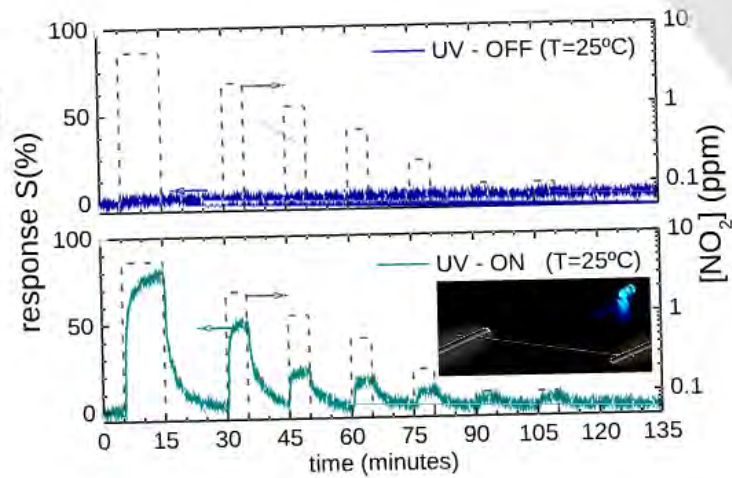
J. Daniel Prades
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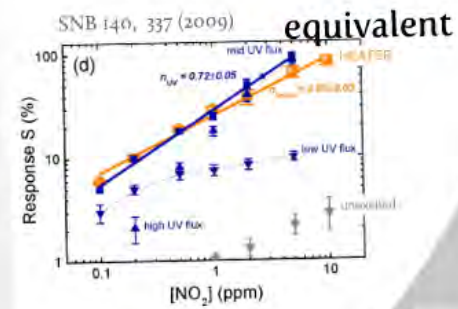
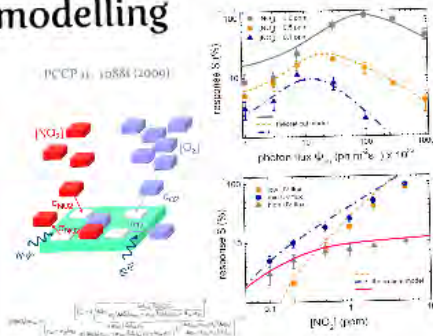
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UV MOX RESISTORS

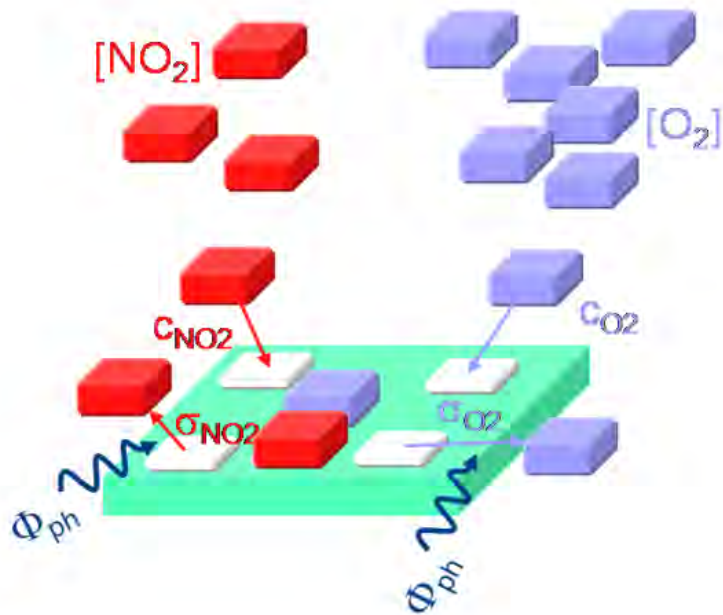


modelling

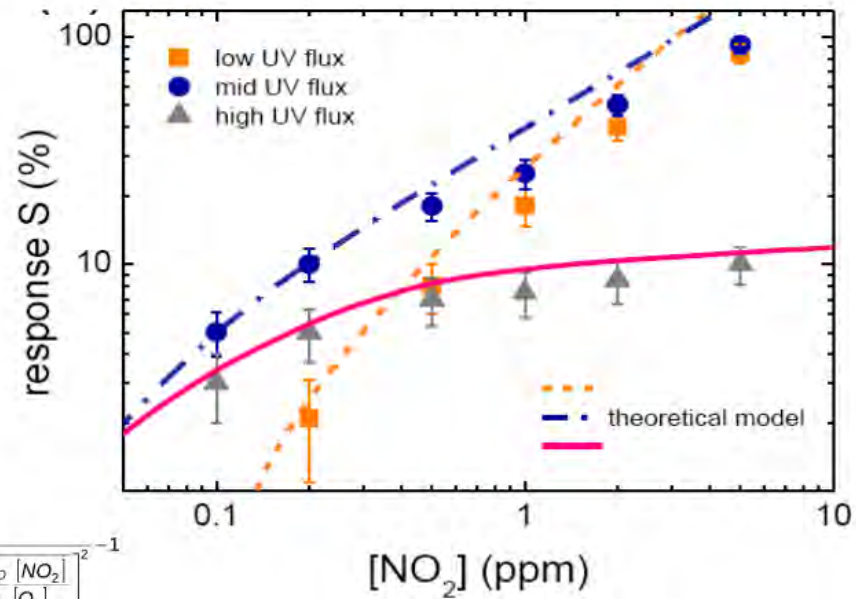
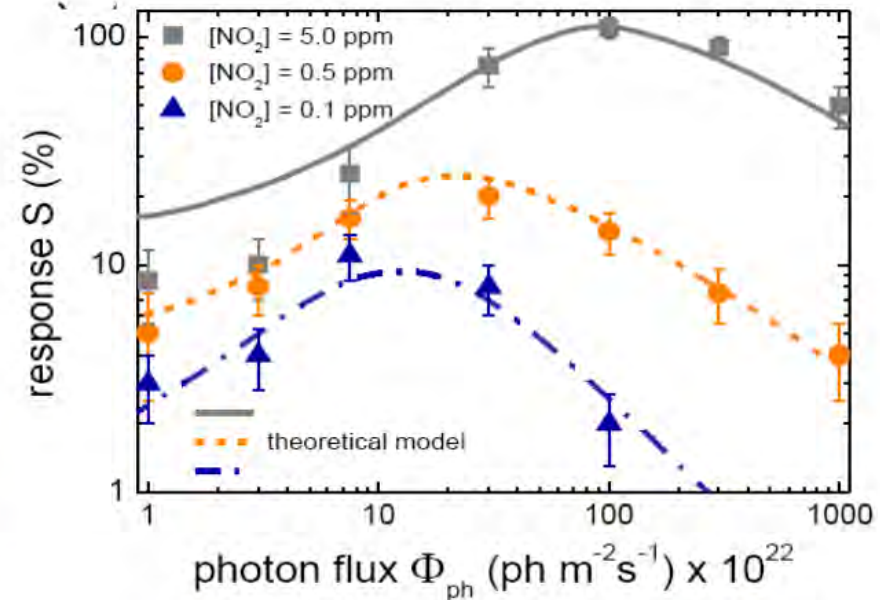


modelling

PCCP II, 1088I (2009)

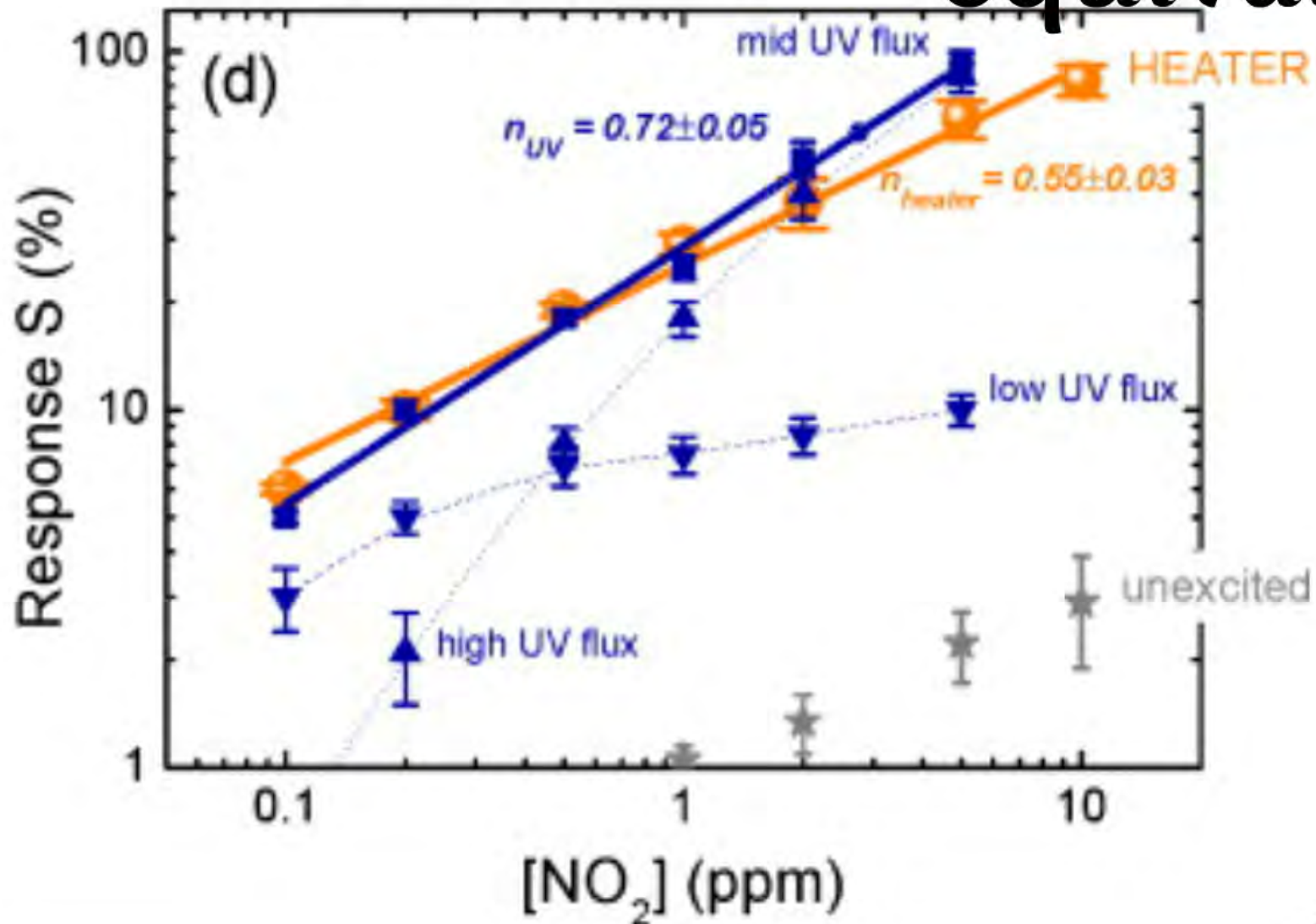


$$S([\text{NO}_2], \Phi_{\text{ph}}) = \frac{\left[r_{\text{nw}} - \alpha \sqrt{\Delta q_{\text{O}_2} \cdot \frac{\Lambda \sigma_{\text{NO}_2} [\text{O}_2]_{\text{SA}} c_{\text{O}_2}}{\sigma_{\text{O}_2} [\text{NO}_2] c_{\text{NO}_2} + \sigma_{\text{NO}_2} ([\text{O}_2]_{\text{SA}} c_{\text{O}_2} + \Phi_{\text{ph}} \sigma_{\text{O}_2})}} \right]^2}{\left[r_{\text{nw}} - \alpha \sqrt{\Delta q_{\text{O}_2} \cdot \frac{\Lambda \sigma_{\text{NO}_2} [\text{O}_2]_{\text{SA}} c_{\text{O}_2}}{\sigma_{\text{O}_2} [\text{NO}_2] c_{\text{NO}_2} + \sigma_{\text{NO}_2} ([\text{O}_2]_{\text{SA}} c_{\text{O}_2} + \Phi_{\text{ph}} \sigma_{\text{O}_2})}} \right]^{-1} \sqrt{1 + \frac{\Delta q_{\text{NO}_2} c_{\text{NO}_2} \sigma_{\text{O}_2} [\text{NO}_2]}{\Delta q_{\text{O}_2} \sigma_{\text{NO}_2} c_{\text{O}_2} [\text{O}_2]_{\text{SA}}}}$$

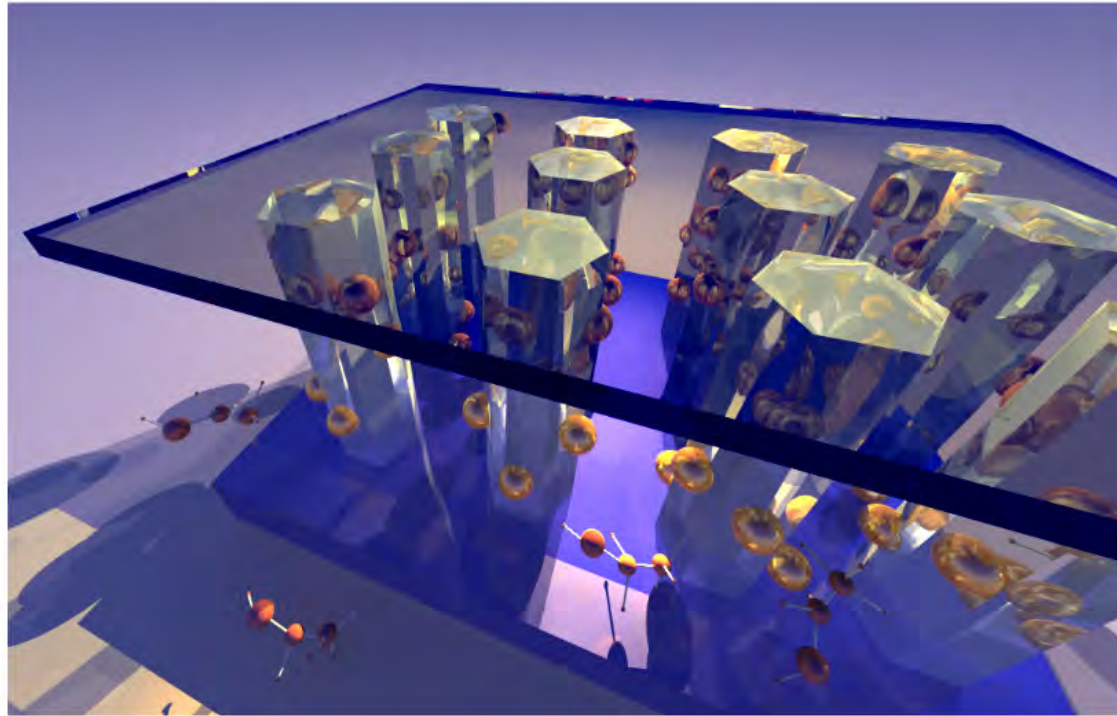


SNB I40, 337 (2009)

equivalent



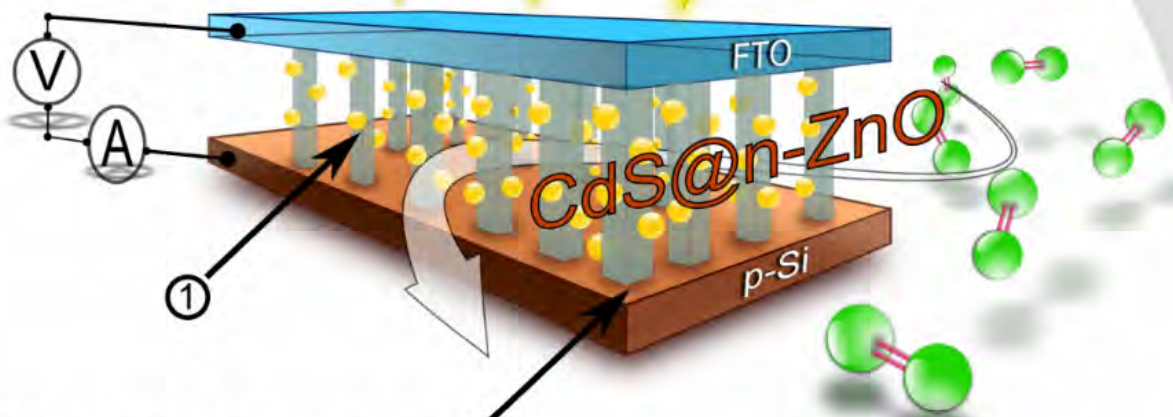
Solar Diode Sensor



M. Hoffmann, J.D. Prades, A.E. Gad, H. Shen et al.,
EU-Patent Nr.: III79783.3.

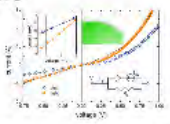
HOW?

solar irradiation

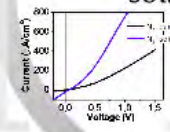


- ① CdS@n-ZnO sensor
- ② n-ZnO/p-Si solar cell

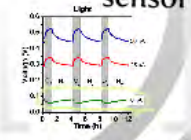
diode



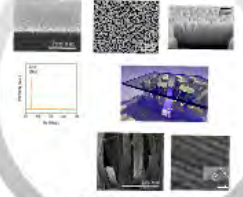
solar



sensor



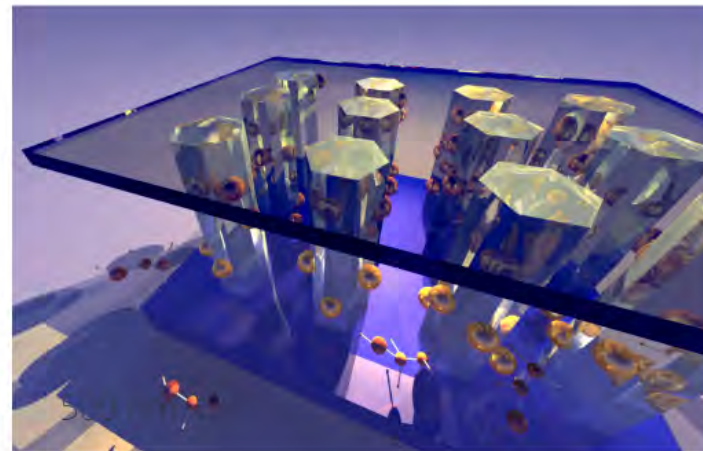
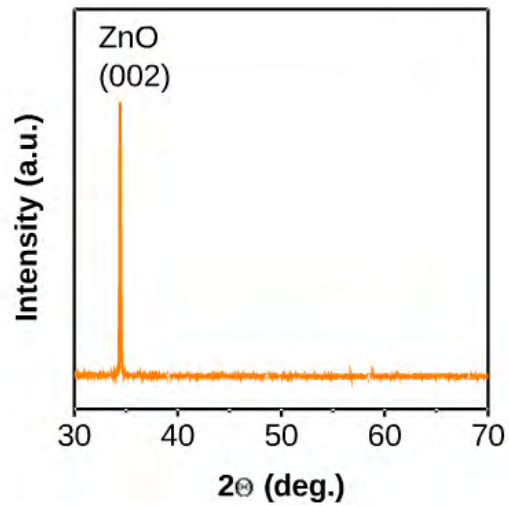
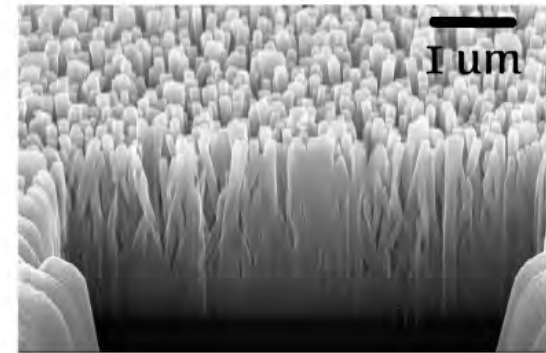
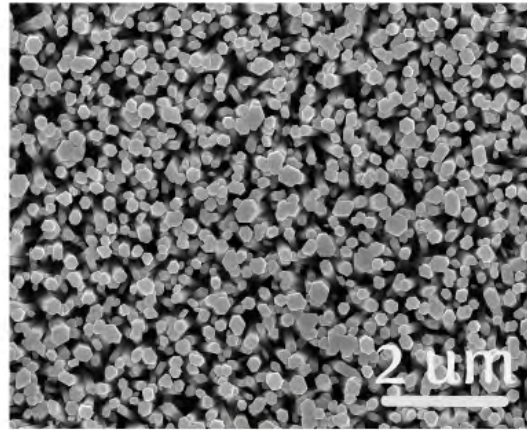
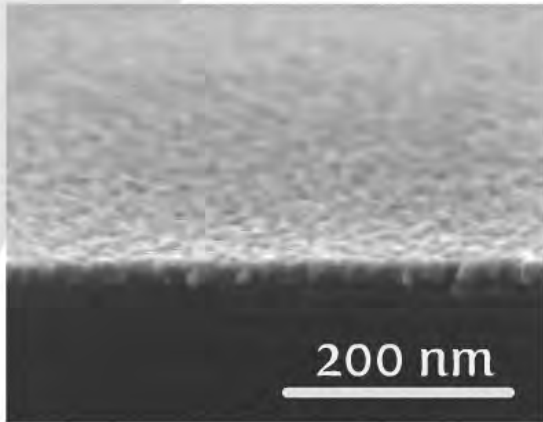
n-ZnO nanowires

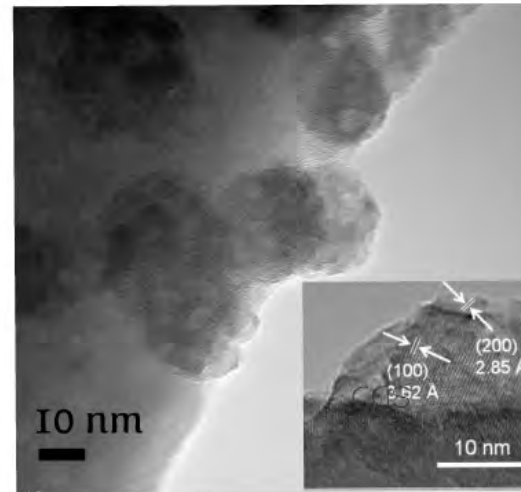
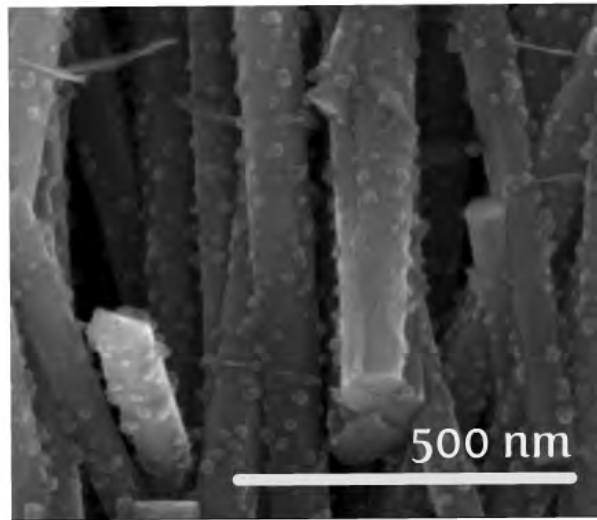
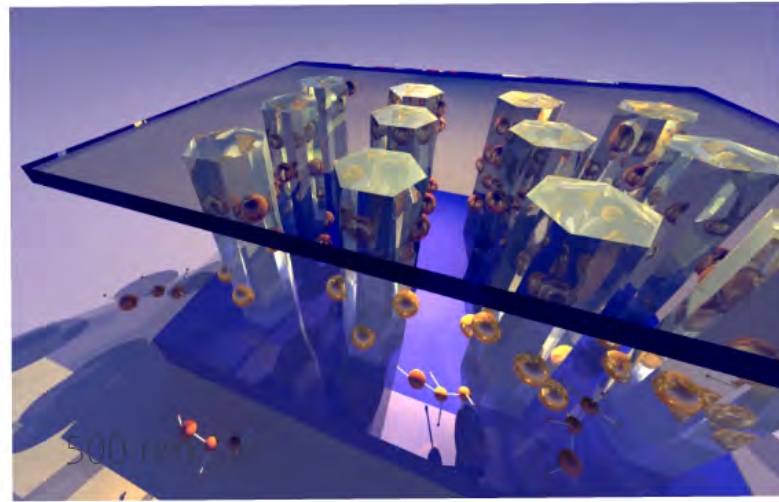
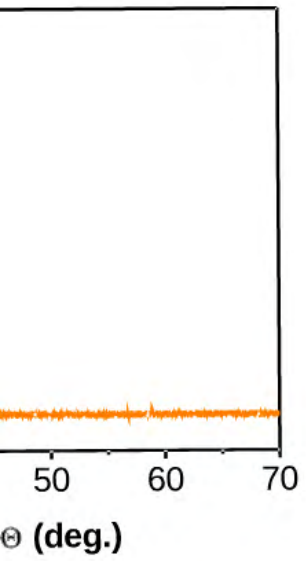


CdS@n-ZnO QDs



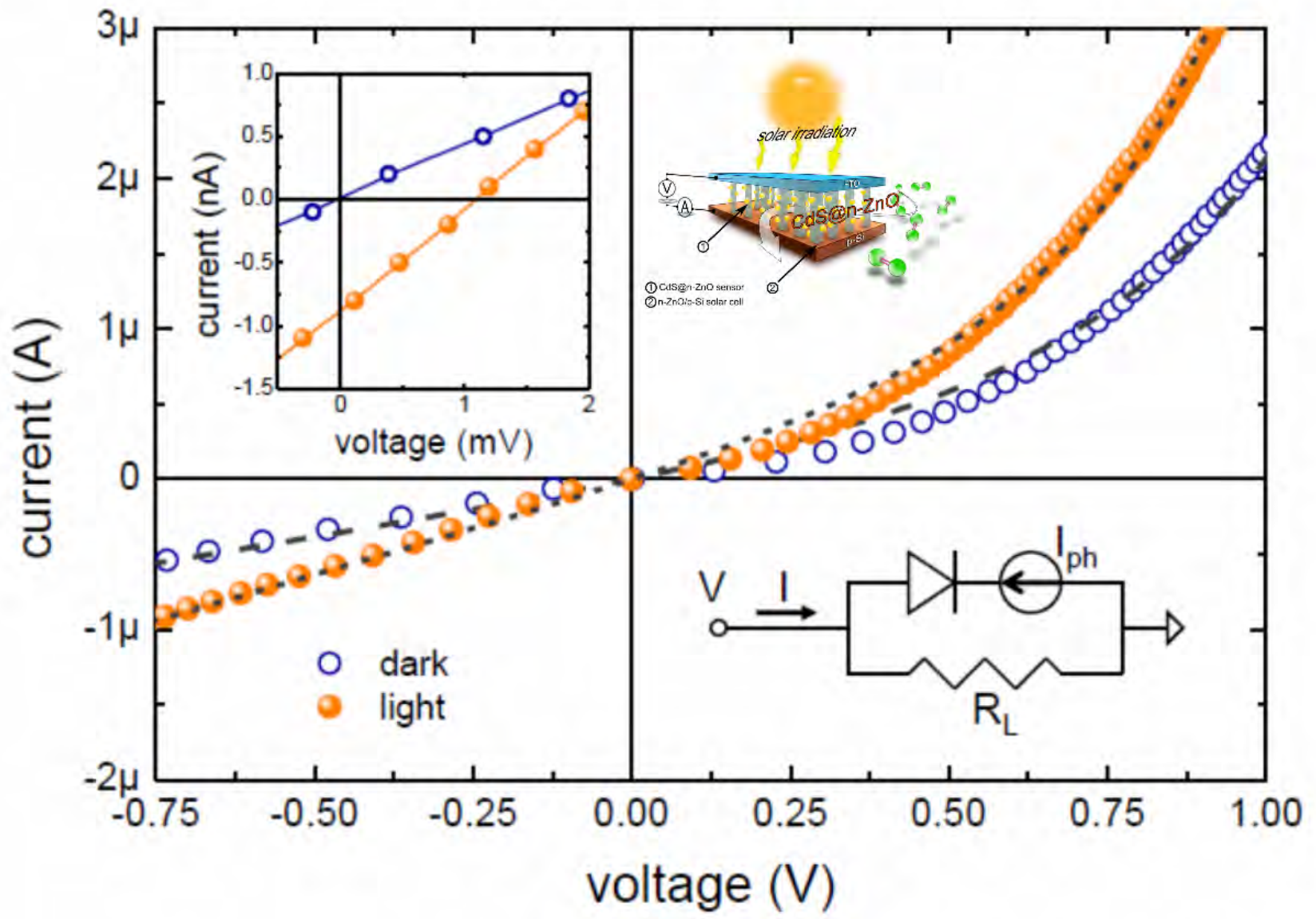
n-ZnO nanowires



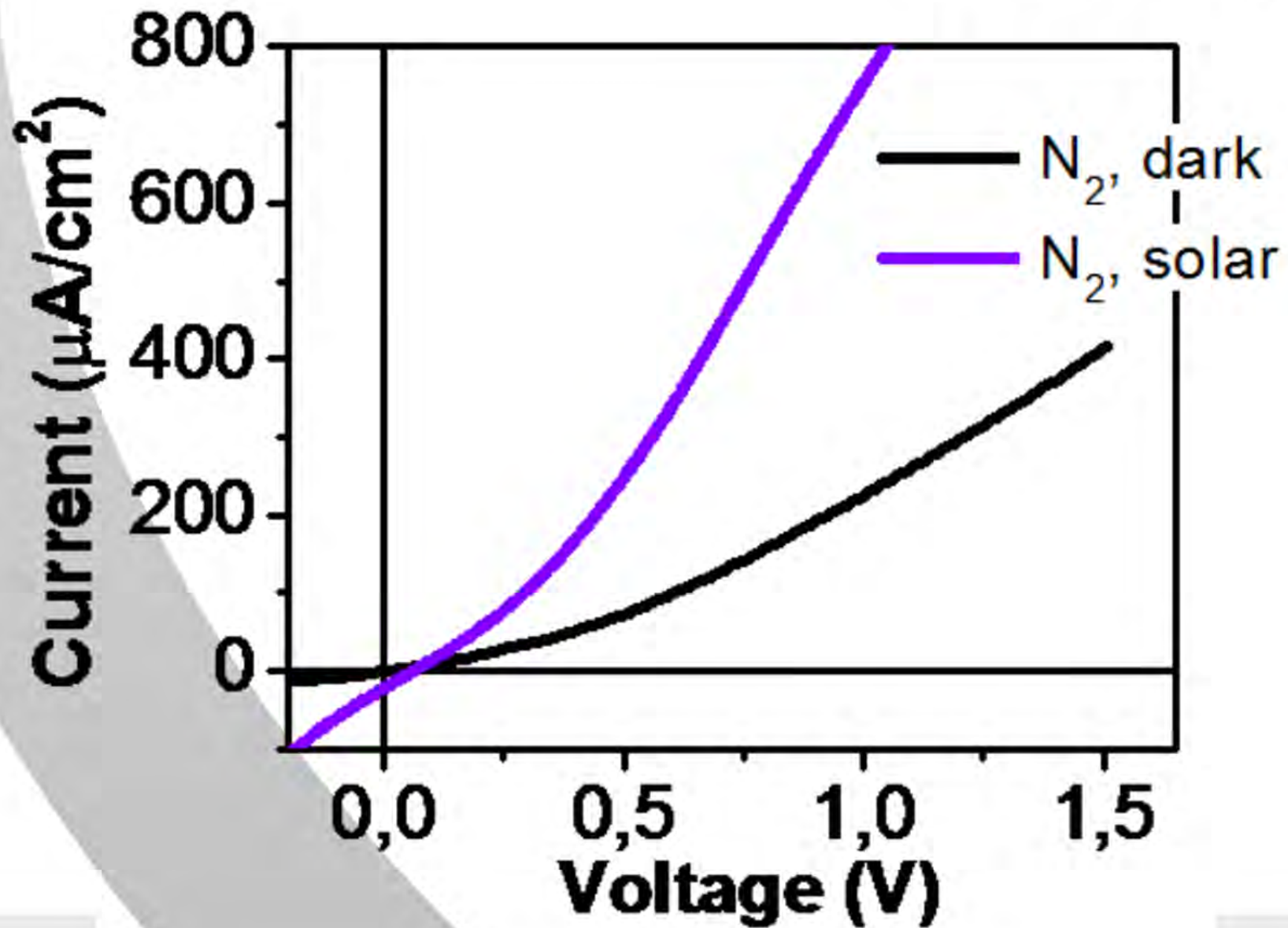


CdS@n-ZnO QDs

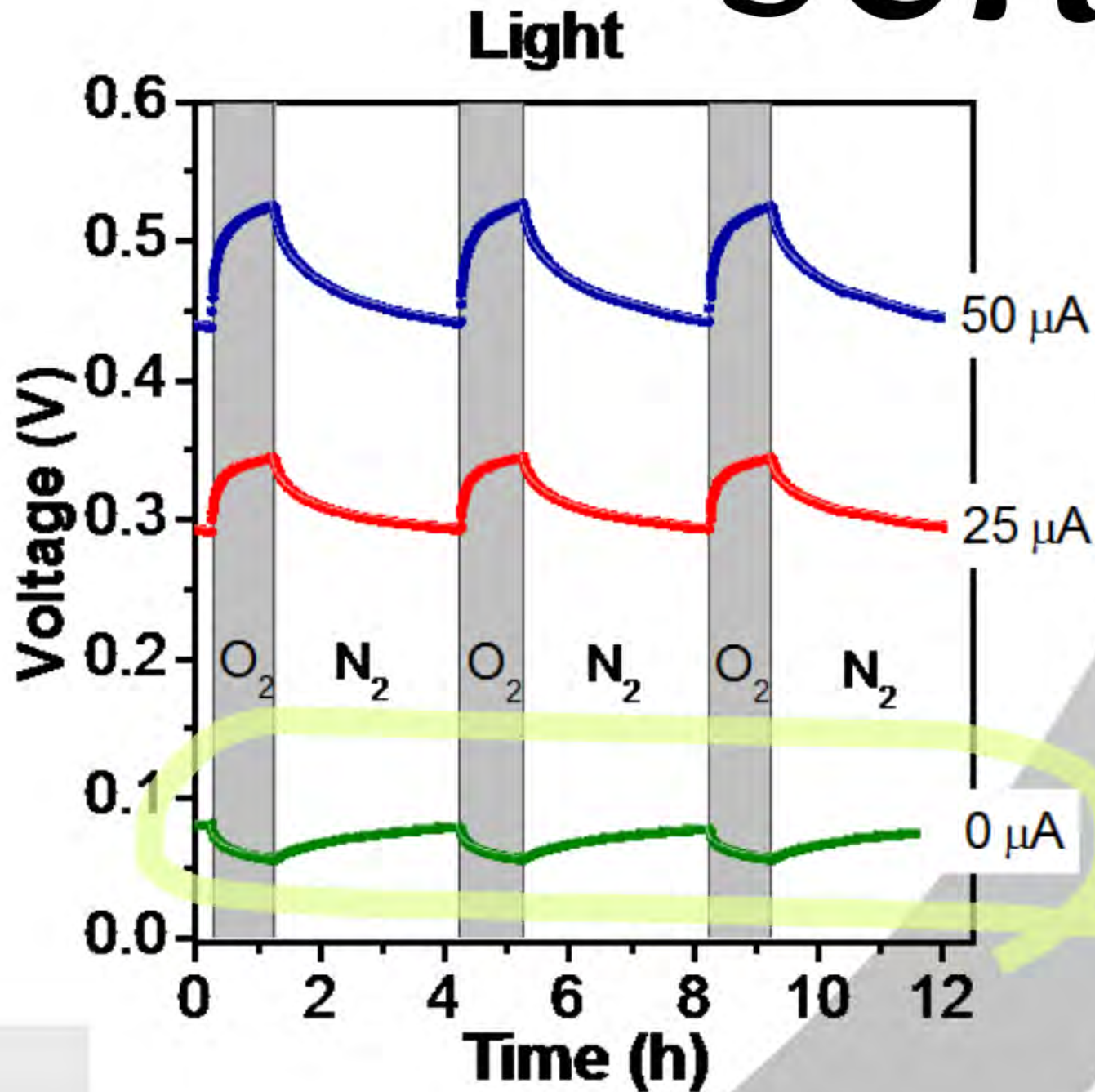
ode



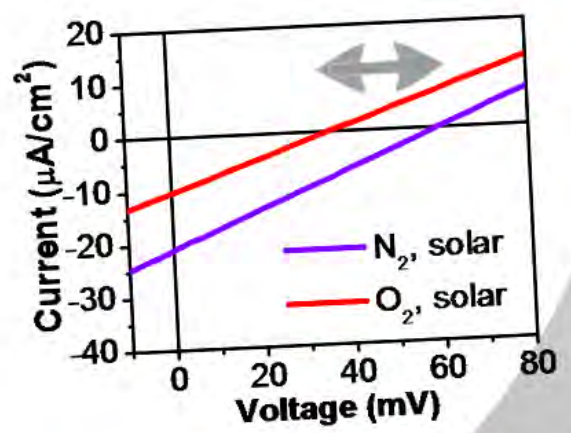
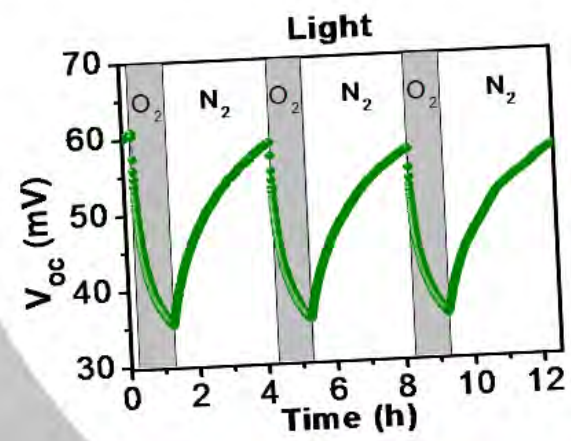
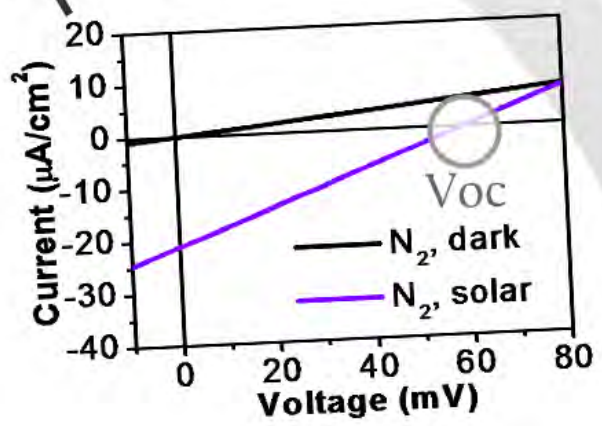
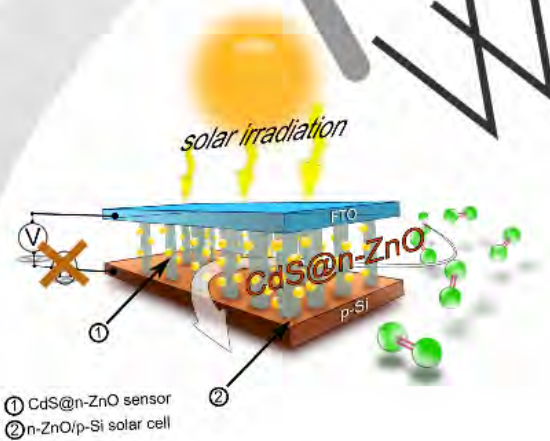
solar



sensor

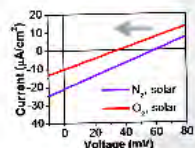
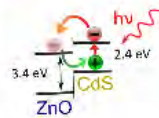
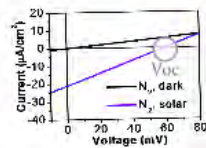
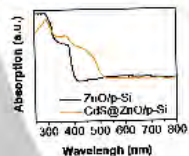
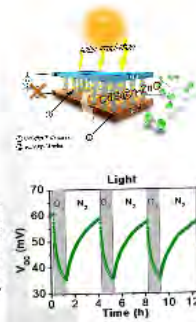
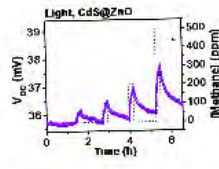
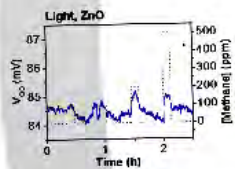


What?

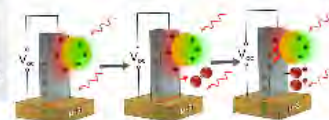


zero power

Why?

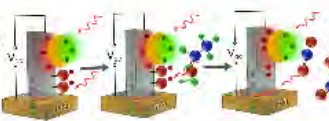


oxidizing gases N_D

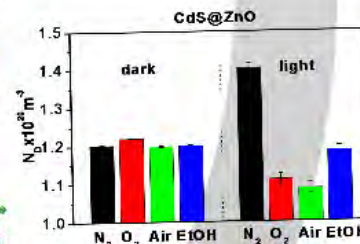


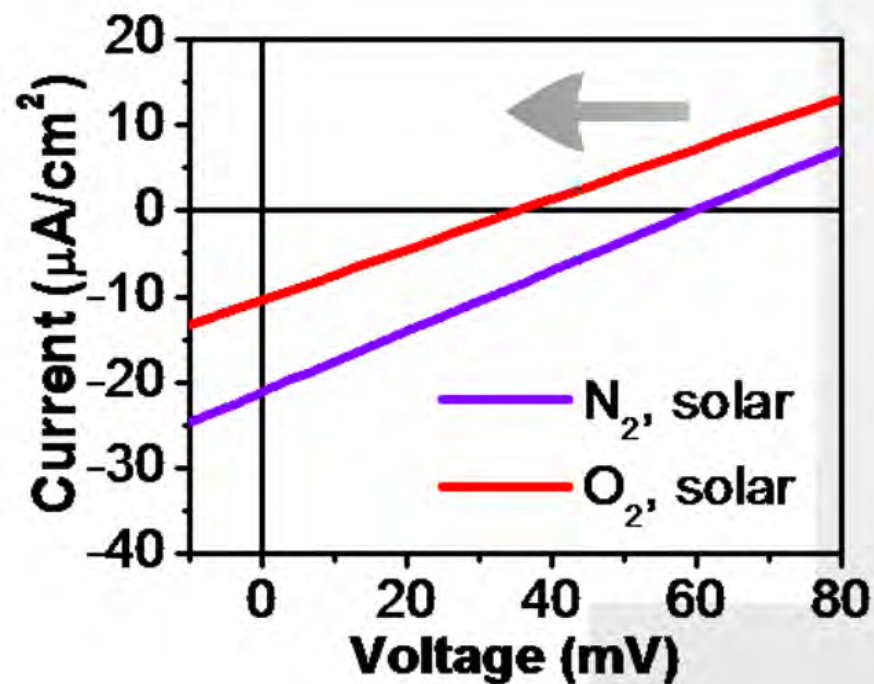
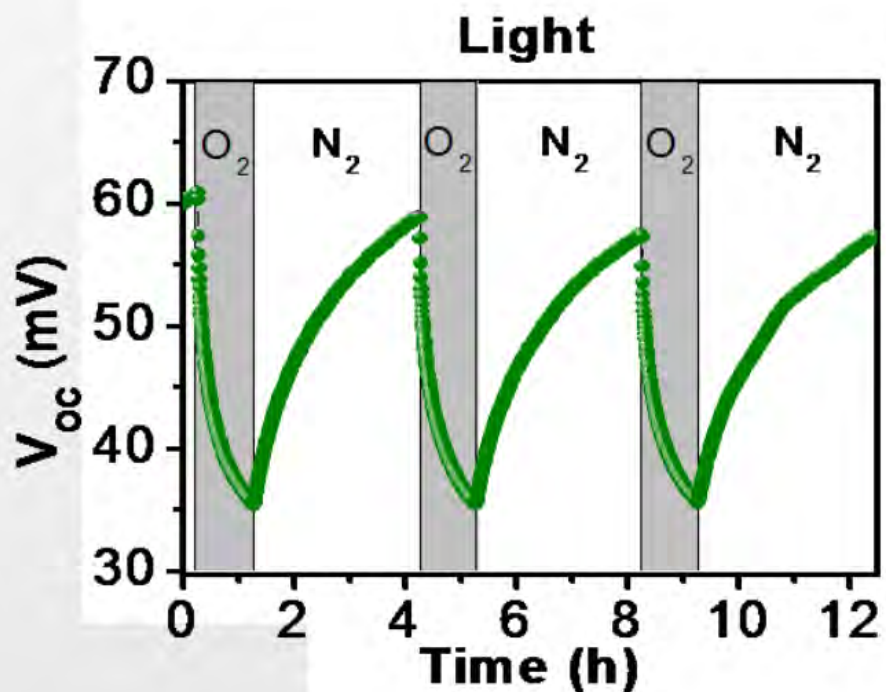
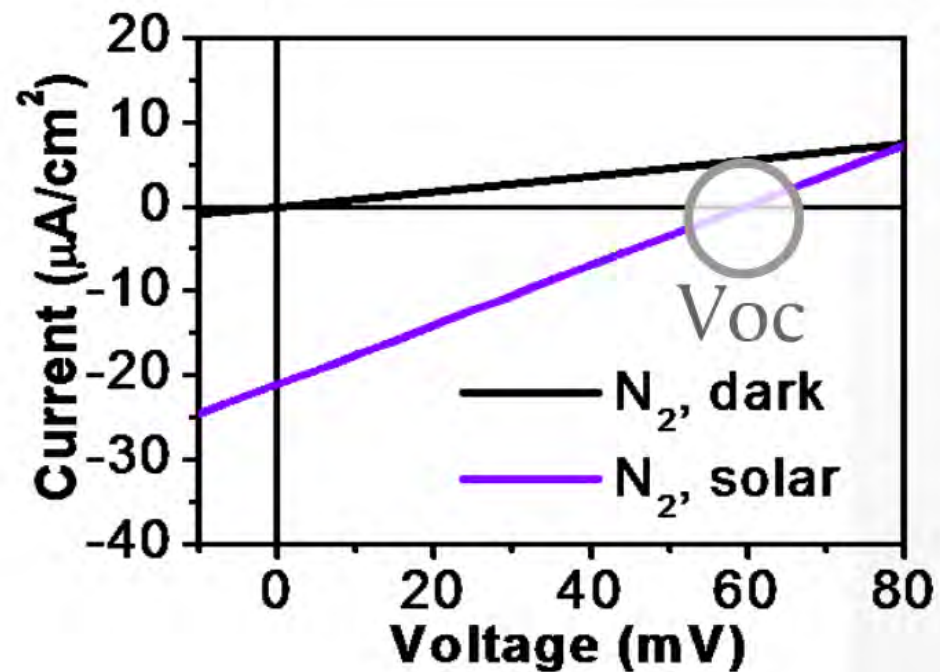
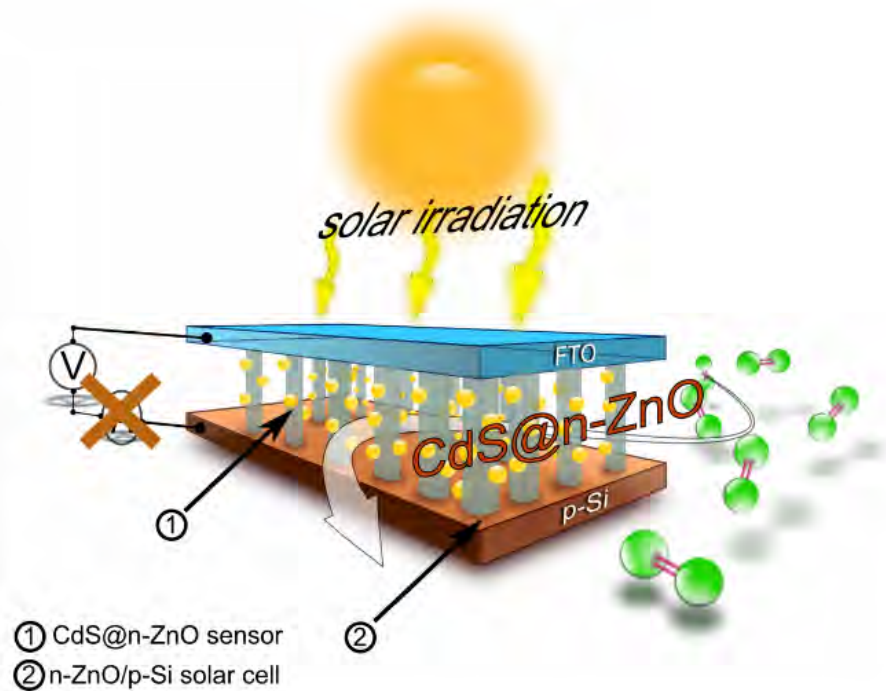
$$V_{oc} = \frac{kT}{q} \ln \left(\frac{N_D^{ZnO} N_A^{Si}}{N_i^{ZnO} N_i^{Si}} \right)$$

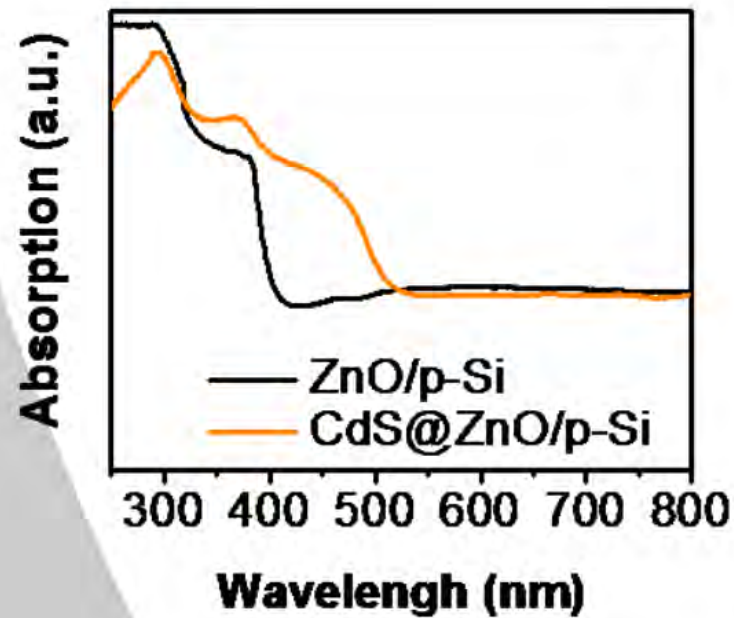
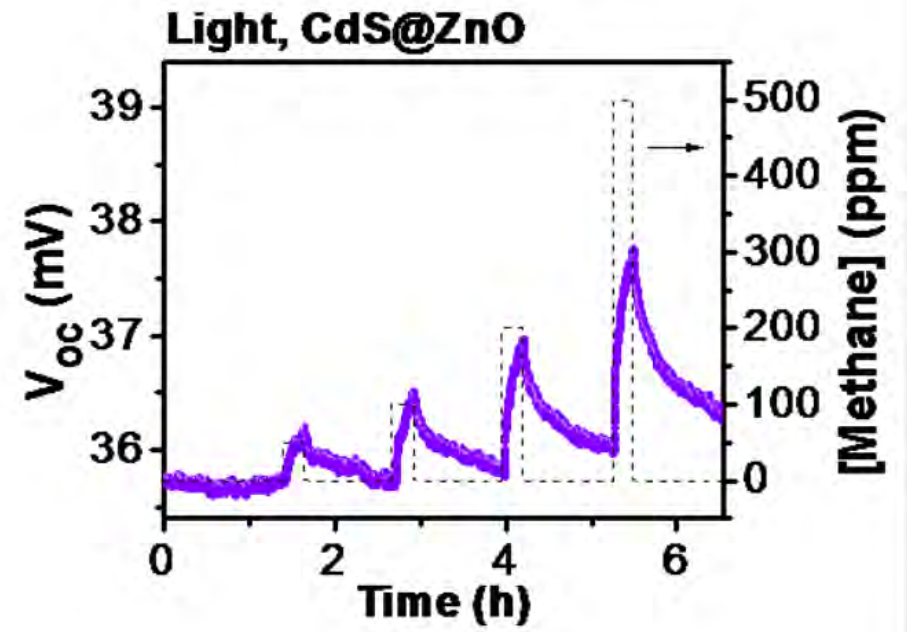
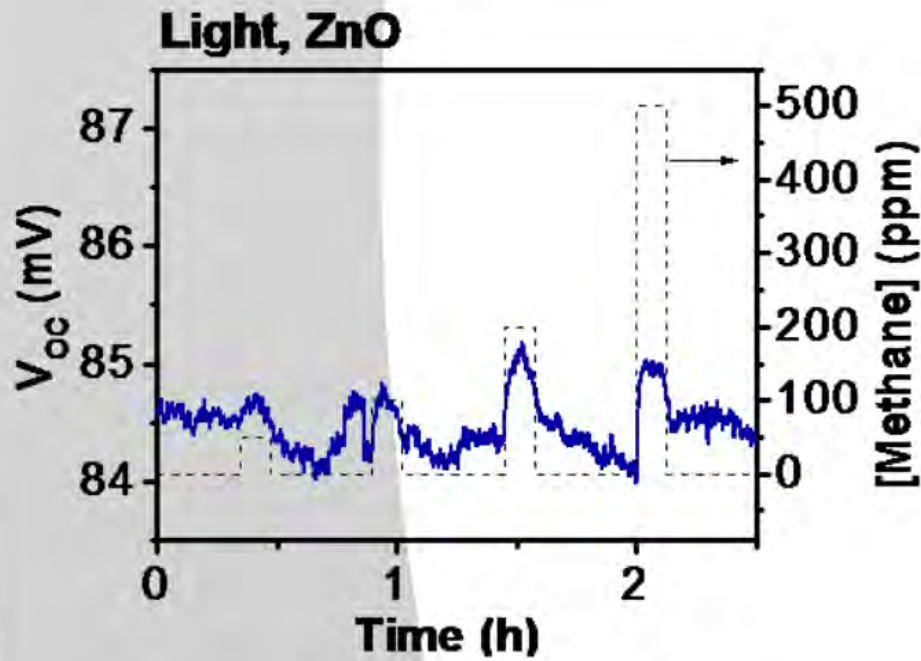
$$V_{oc} \propto V_{oc}$$

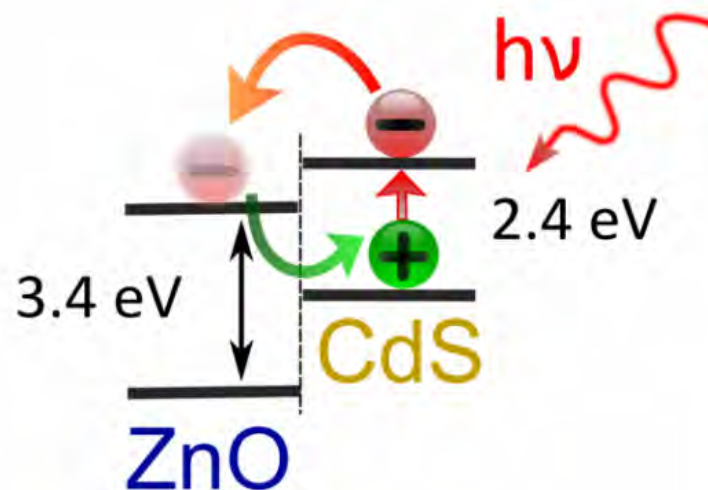
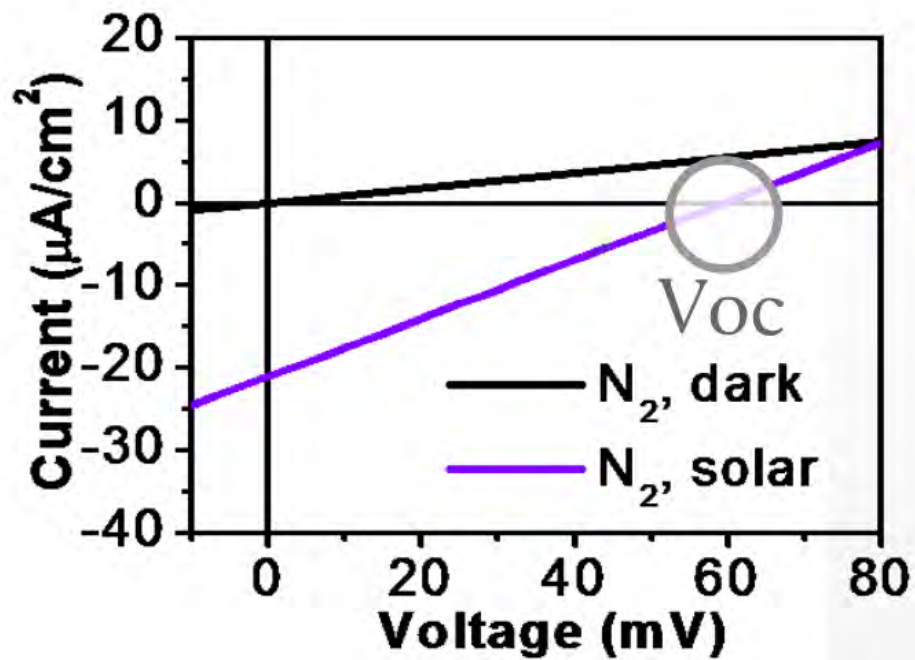
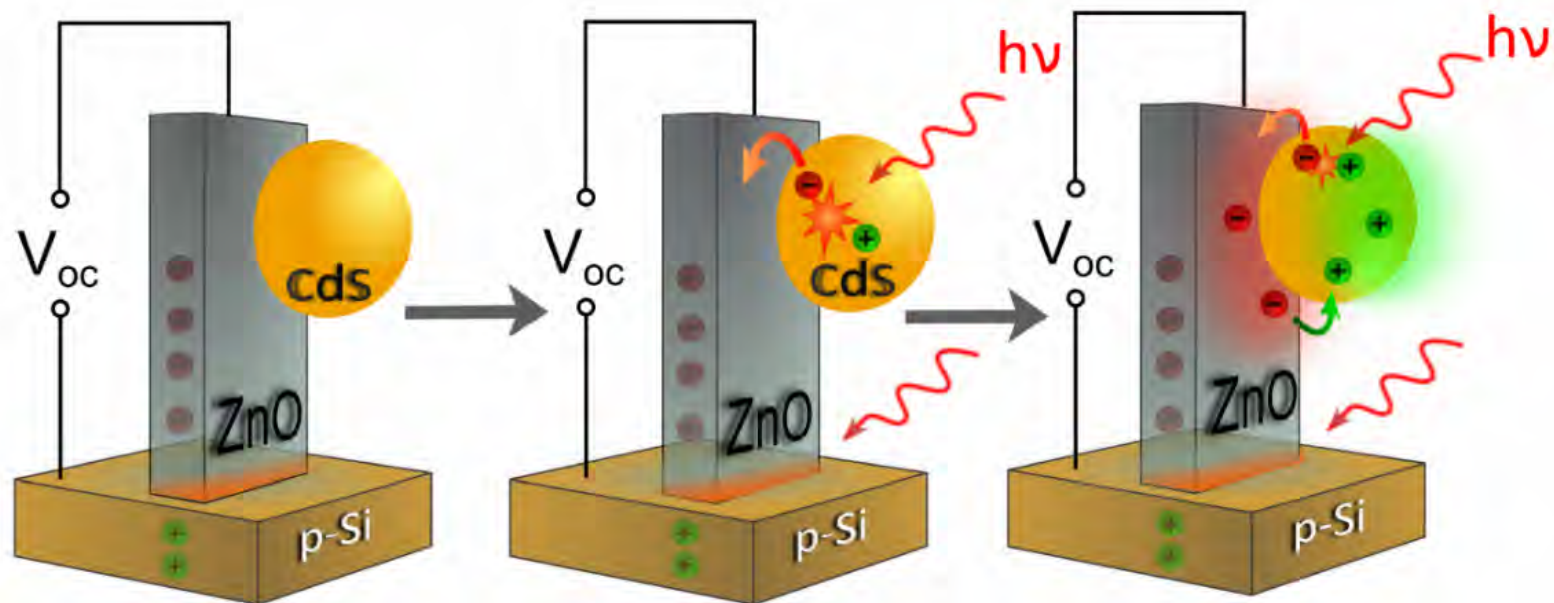


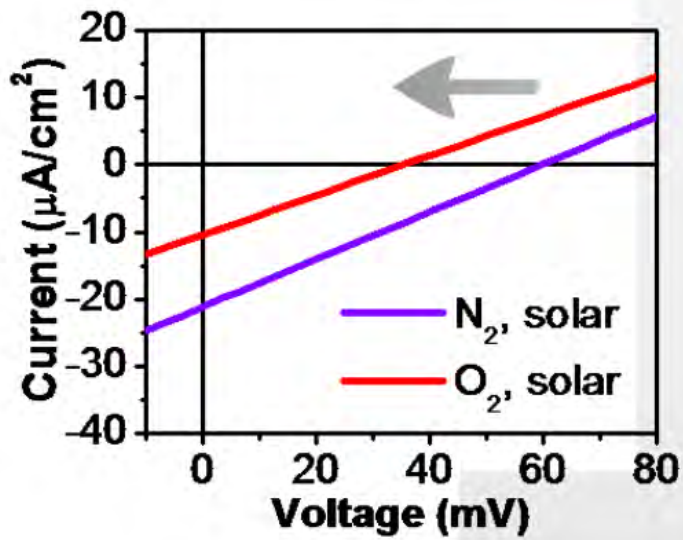
reducing gases N_D



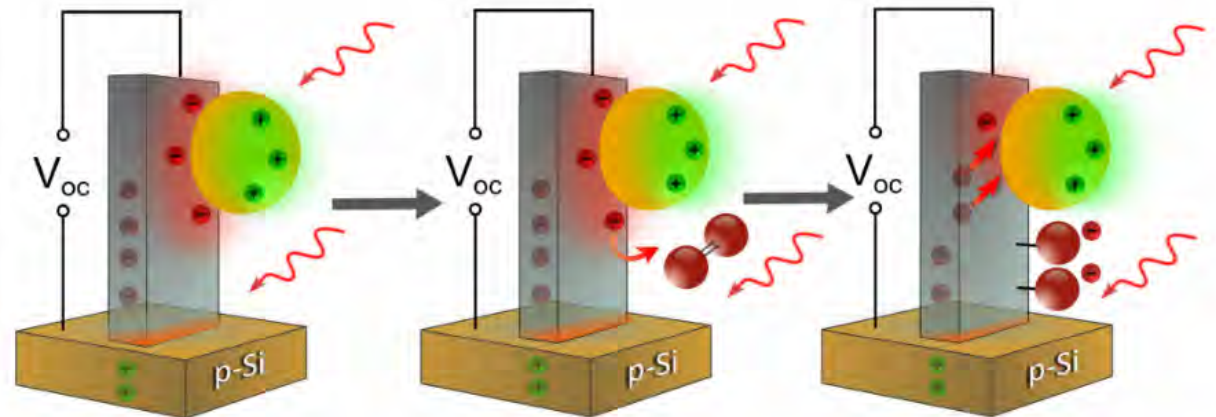






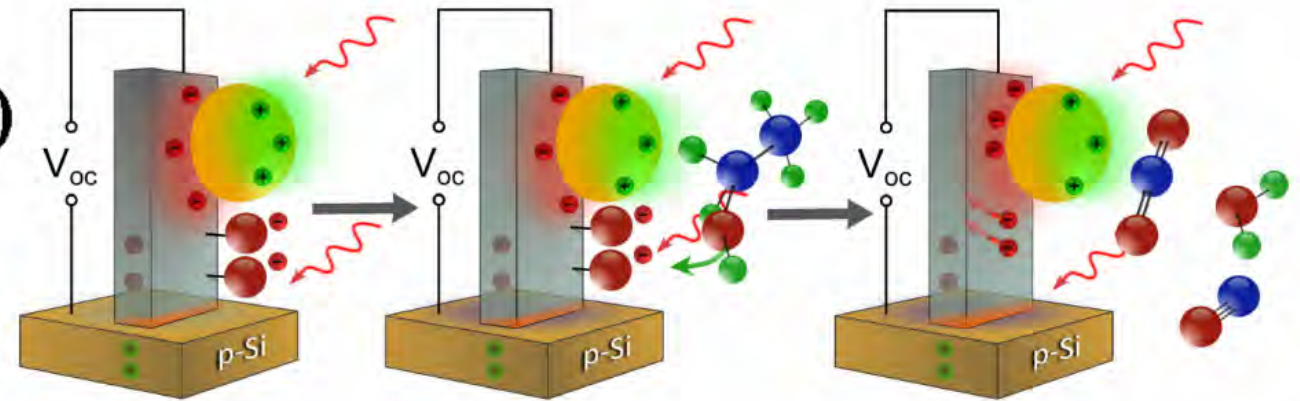
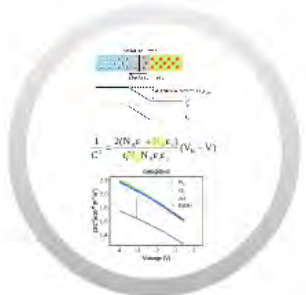


oxygenating gases N_D ↓



$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_D^{ZnO} N_A^{Si}}{N_i^{ZnO} N_i^{Si}}\right)$$

$$V_{bi} \propto V_{oc}$$

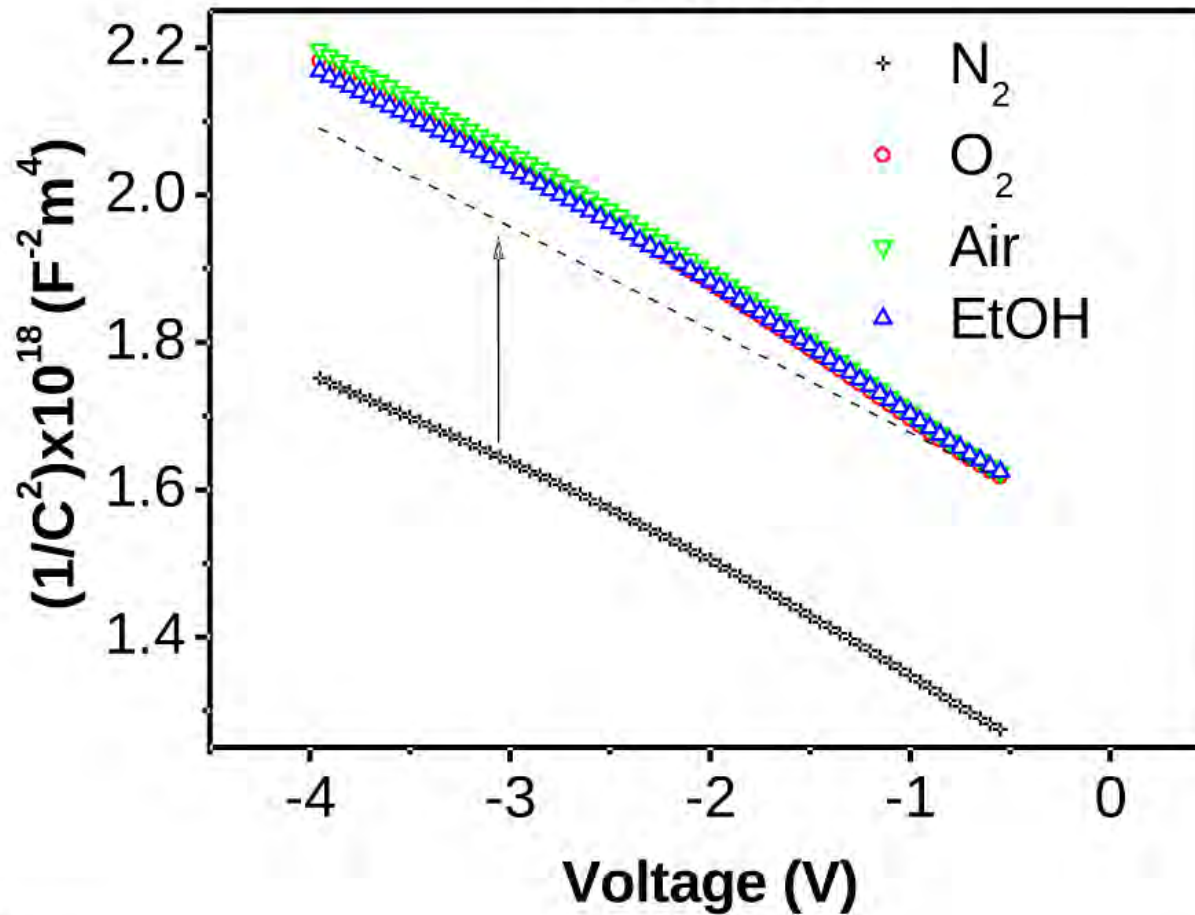


reducing gases N_D ↑

N × 10²⁰ m⁻³

$$\frac{1}{C^2} = \frac{2(N_A \epsilon_1 + N_D \epsilon_2)}{q N_D N_A \epsilon_1 \epsilon_2} (V_{bi} - V)$$

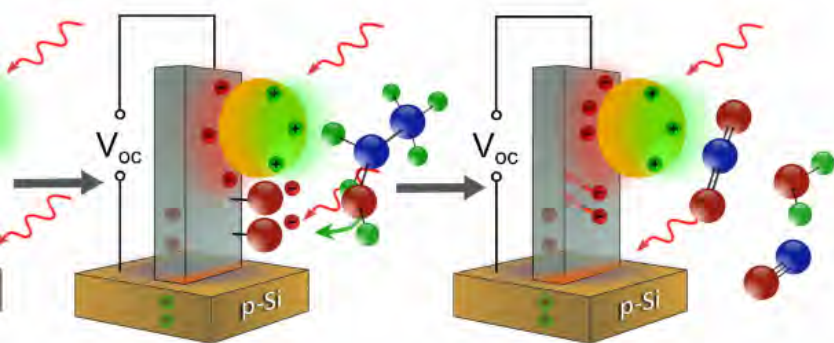
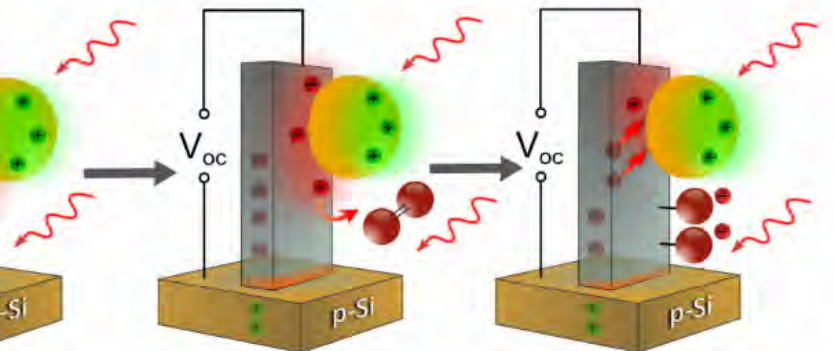
CdS@ZnO



ZnO

oxidizing gases

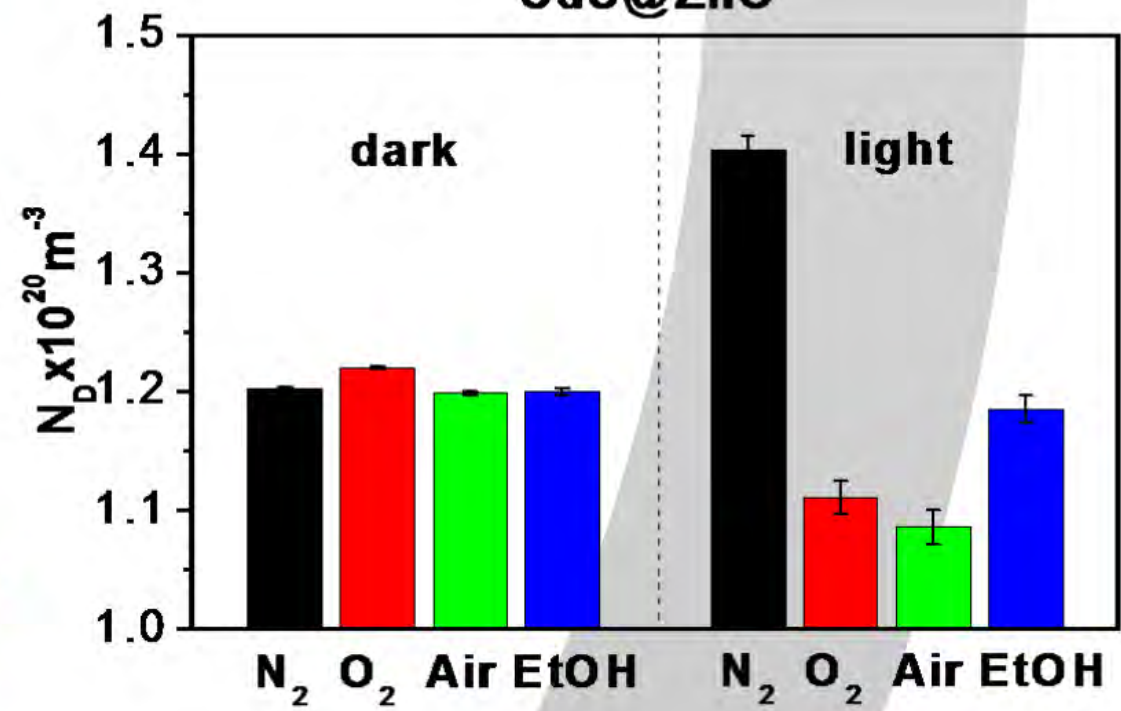
N_D



reducing gases

N_D

CdS@ZnO



Nanowires for Low Power Consumption Gas Sensors



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viii intl. workshop in semiconductor gas sensors
sept. 2012 krakow





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