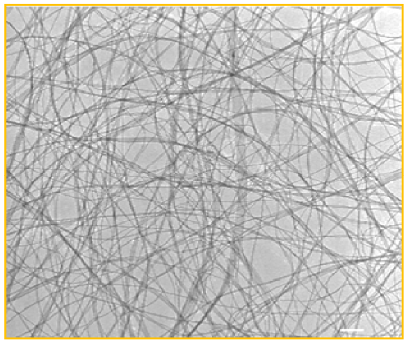
第 276 期
凝聚态物理.北京大学论坛

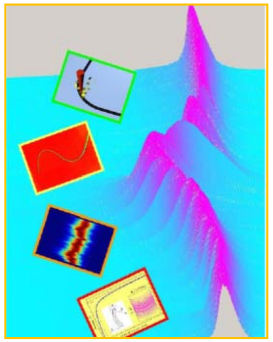
Semiconductor Nanowires: Bridging the Macroscopic and Microscopic Worlds

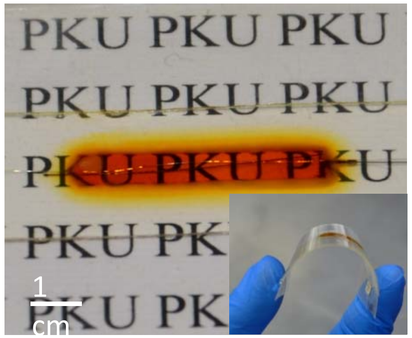
俞大鹏

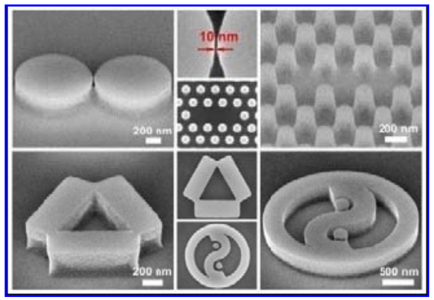
2013-03-08

纳米结构与低维物理 实验室









Laboratory for Nanostructures and Low-Dimensional Physics

Prof. Dapeng YU
Group Head

Prof. Xiaosong WU

Prof. Qing ZHAO
Asso.

Prof. Jin LU, Asso.

Prof. Zhimin LIAO Asso.

Dr. Fang LIN

1. VSL/PVD-directed growth of semiconductor nanowires and other 2-D nanomaterials (Graphene, Topological Insulators); p-type and magnetic doping/modification of the nanowires;
2. Transport and opo-electronic property exploration of the nanowires and graphene;
3. Nanowire filed emitters; UV detection and solar cells based on nanowires; single DNA detection/sequencing based on solid state nanopore.
4. Theoretical calculation of the low-dimensional nanostructures.

What is Nanoscience and Nanotechnology?

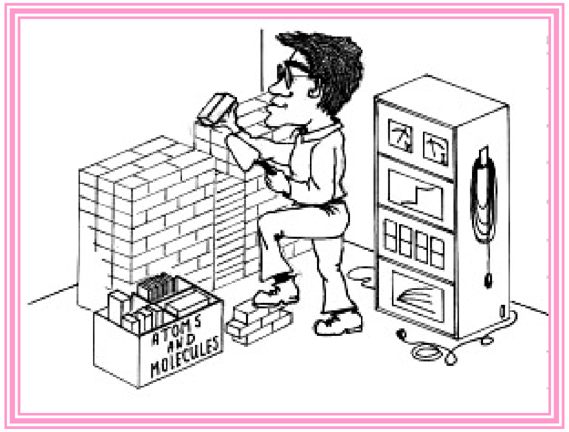
在原子、分子、大分子（1~100nm）尺度上研究物质的特性和相互作用的科学（nanoscience），以及利用这些特性进行纳米尺度的精确操纵、加工（nanotechnology）和制造应用等方面的技术。

Nanoscience

the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.

Nanotechnology

the manipulation, precision placement, measurement, modelling or manufacture of sub -100 nanometer scale matter.



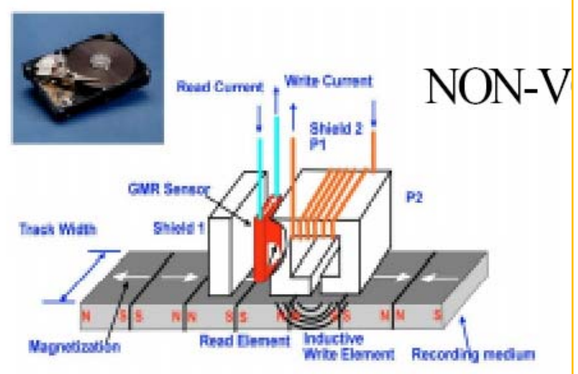
Ability to: 在原子、分子尺度上操纵物质

This is truly Nanoscience/Technology

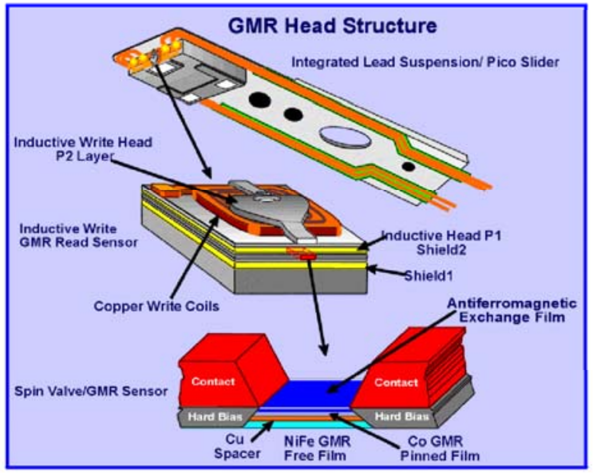
- 2007年10月9日 瑞典皇家科学院诺贝尔奖委员会将2007年度诺贝尔物理奖授予法国科学家艾尔伯-费尔和德国科学家皮特-克鲁伯格，以表彰他们发现的贡献。

Albert Fert 克鲁伯格

Giant Magnetoresistance (GMR)
Spintronics



Magnetic recording process.



Commercial IBM giant magnetoresistance read head.

VOLUME 61, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1988

Giant Magnetoresistance of (001) Fe/(001) Cr Magnetic Superlattices

M. N. Baibich,[a] J. M. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff
Laboratoire de Physique des Solides, Université Paris-Sud, F-91405 Orsay, France

P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas
Laboratoire Central de Recherches, Thomson CSF, B.P. 10, F-91401 Orsay, France
(Received 24 August 1988)

We have studied the magnetoresistance of (001)Fe/(001)Cr superlattices prepared by molecular-beam epitaxy. A huge magnetoresistance is found in superlattices with thin Cr layers: For example, with $t_{Cr}=9$ Å, at $T=4.2$ K, the resistivity is lowered by almost a factor of 2 in a magnetic field of 2 T. We ascribe this giant magnetoresistance to spin-dependent transmission of the conduction electrons between Fe layers through Cr layers.

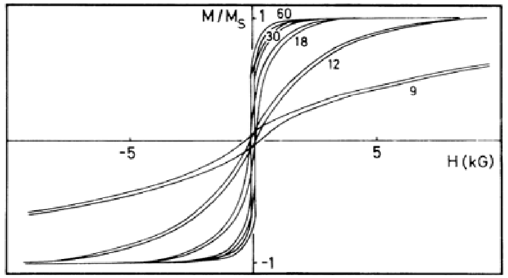


FIG. 1. Hysteresis loops at 4.2 K with an applied field along [110] in the layer plane for several (001)Fe/(001)Cr superlattices: [(Fe 60 Å)/(Cr 60 Å)]$_5$, [(Fe 30 Å)/(Cr 30 Å)]$_{10}$, [(Fe 30 Å)/(Cr 18 Å)]$_{30}$, [(Fe 30 Å)/(Cr 12 Å)]$_{10}$, [(Fe 30 Å)/(Cr 9 Å)]$_{40}$, where the subscripts indicate the number of bilayers in each sample. The number beside each curve represents the thickness of the Cr layers.

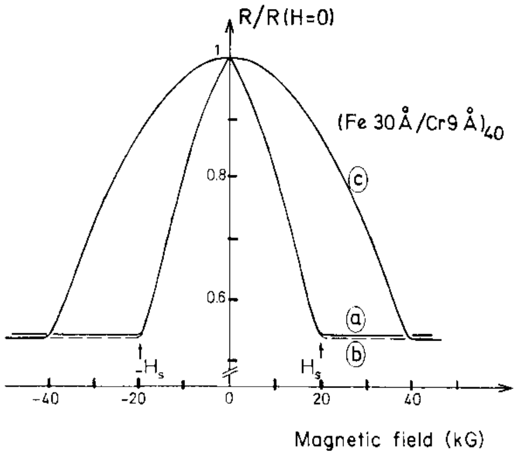


FIG. 2. Magnetoresistance of a [(Fe 30 Å)/(Cr 9 Å)]$_{40}$ superlattice of 4.2 K. The current is along [110] and the field is in the layer plane along the current direction (curve *a*), in the layer plane perpendicular to the current (curve *b*), or perpendicular to the layer plane (curve *c*). The resistivity at zero field is 54 $\mu\Omega$ cm. There is a small difference between the curves in increasing and decreasing field (hysteresis) that we have not represented in the figure. The superlattice is covered by a 100-Å Ag protection layer. This means that the magnetoresistance of the superlattice alone should be slightly higher.

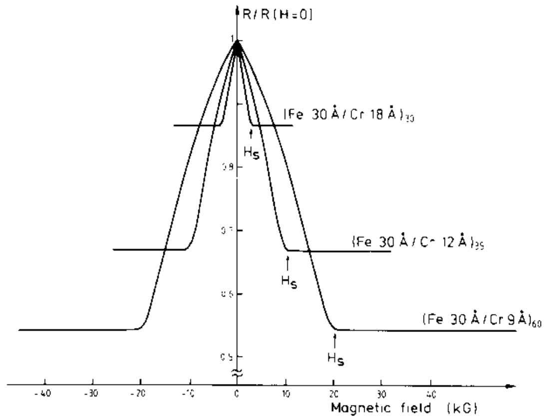


FIG. 3 Magnetoresistance of three Fe/Cr superlattices at 4.2 K. The current and the applied field are along the same [110] axis in the plane of the layers.

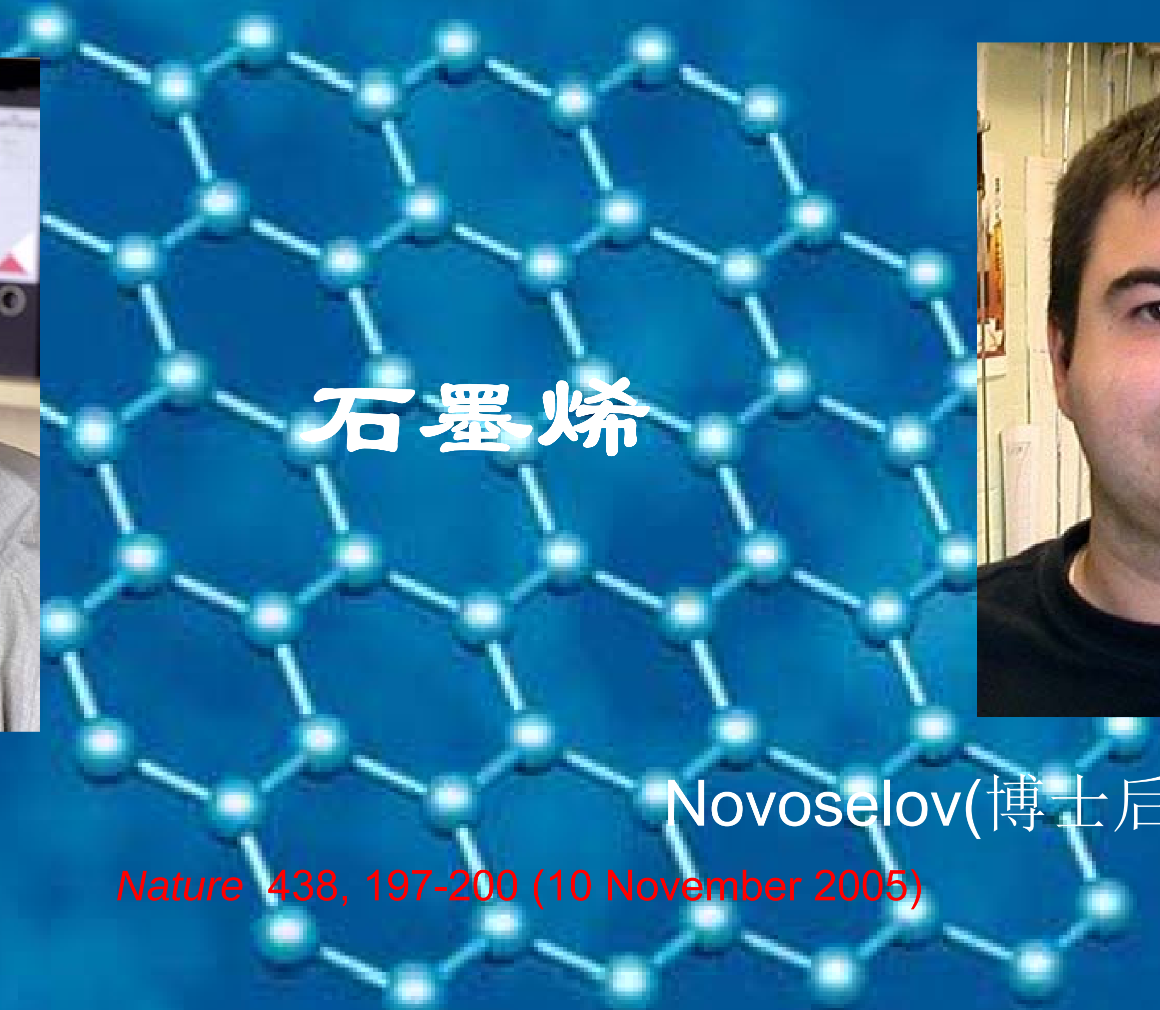
H Index: 62

被引频次: 4,965次

2004

This is truly Nanoscience/Technology

The Nobel prize in physics 2010



Geim

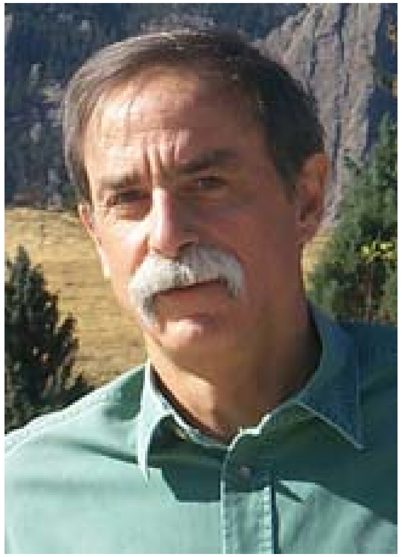
Novoselov(博士后期间)

Nature 438, 197-200 (10 November 2005)

全碳电子学器件是人类追求的梦想

This is truly Nanoscience/Technology

Manipulation in Quantum Optics



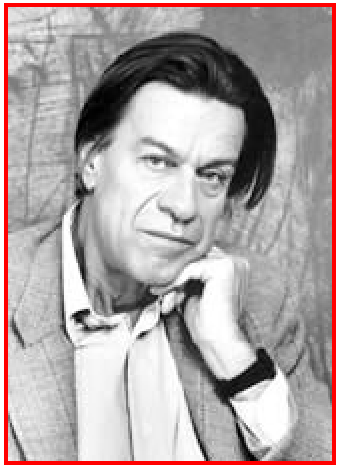
Serge Haroche **David J. Wineland**

Ecole Normale Supérieure in Paris **University of Colorado Boulde**

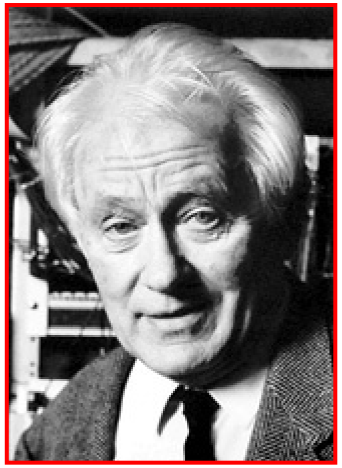
for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems.

法国－物理学强国

21年内5个Nobel物理学奖获得者！！！

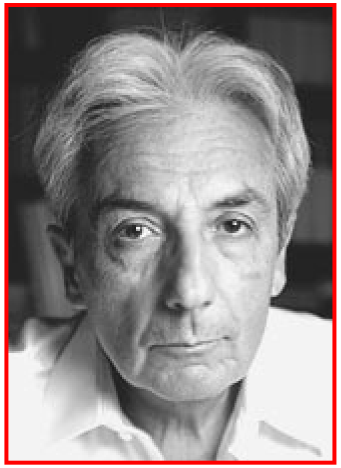


Pierre-Gilles de Gennes



Georges Charpak

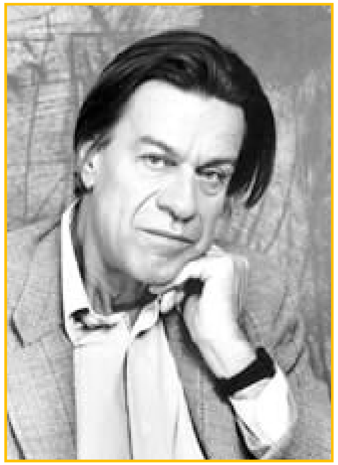
Claude cohen Tannoudji



Albert Fert

Serge Haroche

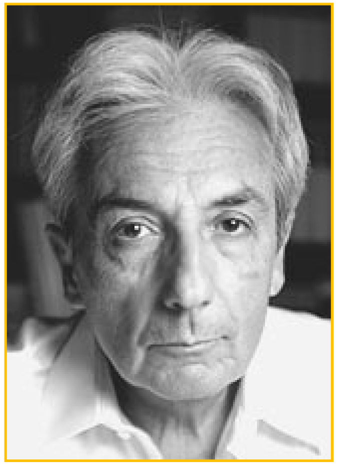
1. 2012, **Serge Haroche**: for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems.
2. 2007, **Albert Fert**: for the discovery of Giant Magnetoresistance .
3. 1997, **Claude cohen Tannoudji**: for development of methods to cool and trap atoms with laser light .
4. 1992, **Georges Charpak**: for his invention and development of particle detectors, in particular the multiwire proportional chamber.
5. 1991, **Pierre-Gilles de Gennes**: for discovering that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers.

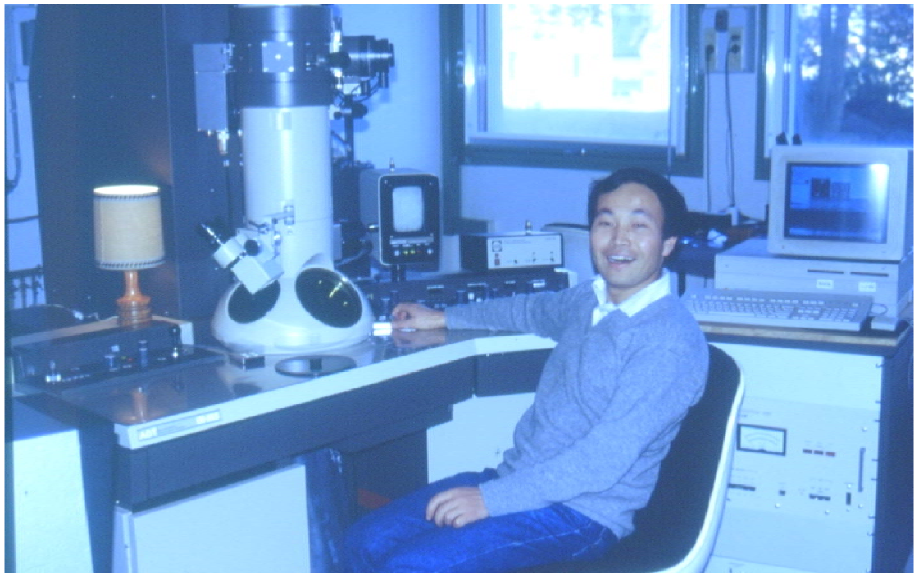


南巴黎大学——固体物理实验室

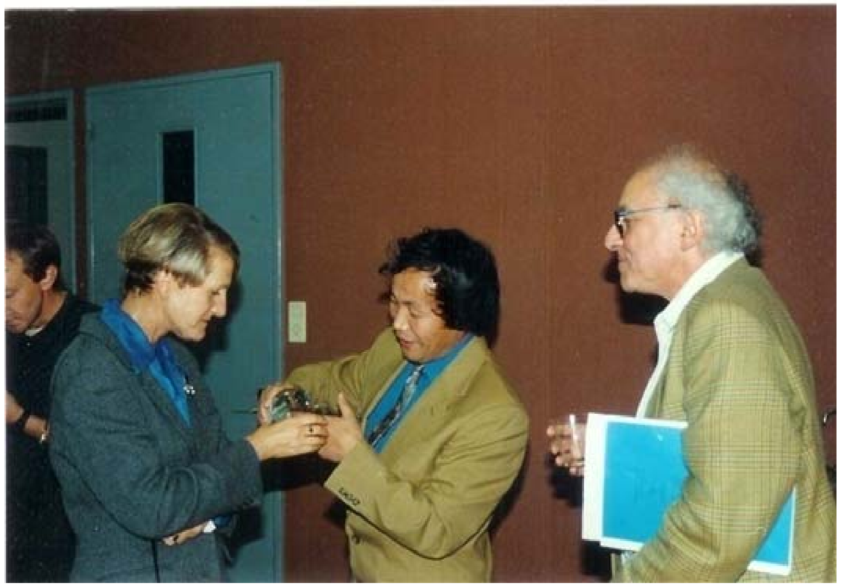
Bâtiment 510, Orsay, UPS

物理学的圣地之一





1992, Université, Paris-Sud



1993年10月6日，博士论文答辩

Outline

- **Why Nanowires?**
- **Our contribution to world research;**
- **Recent Progress in fine nanostructure study via high spatial/energy Cathodoluminescence;**
- **Summary**

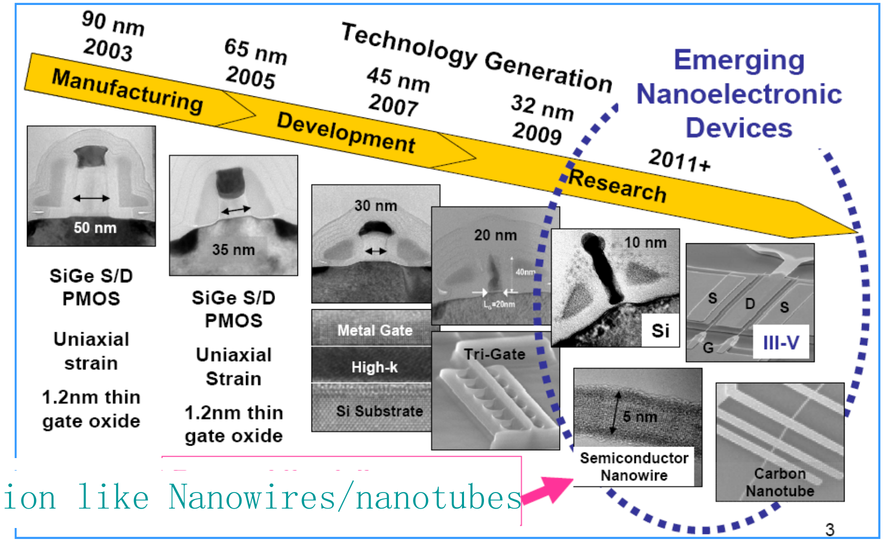
Why Nanowires

- Nanowires: ideal building blocks for nanotechnology
- Our contribution in nanowire research

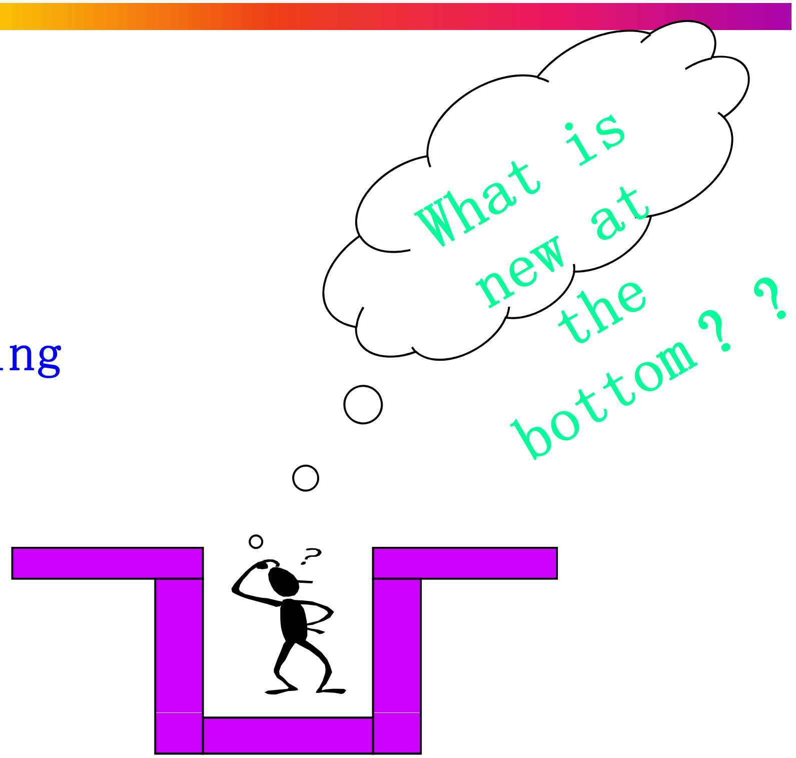
Why Nanowires ?

- 微电子技术迅猛发展的必然产物！
- 认识小尺度世界自然规律的需要

Nanotechnology will extend CMOS scaling



Innovation like Nanowires/nanotubes



$$\lambda_{de} = 2\pi\sqrt{\frac{\hbar^2}{2m^* E}}$$

Newton Mechanics　Featured Physical Length　Quantum Mechanics

Macro(m)　Nanowires as a Bridge　Micro(nm)

What is new of the Nanowires?

1）与量子点相比，纳米线是电荷输运的最小载体；

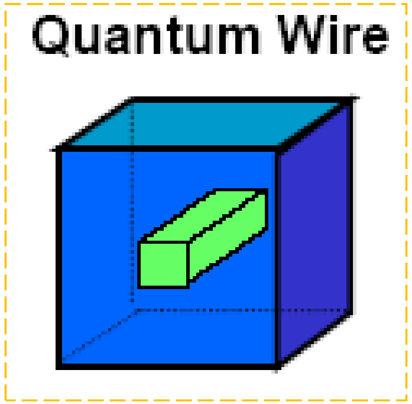
2）与纳米碳管相比，纳米线具有材料选择的多样性；

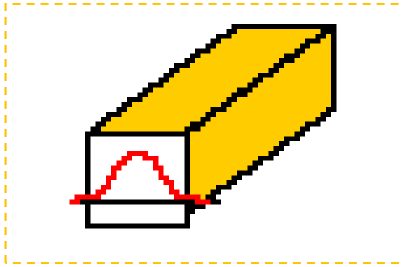
3）与块体材料相比，具有大比表面积和量子效应；

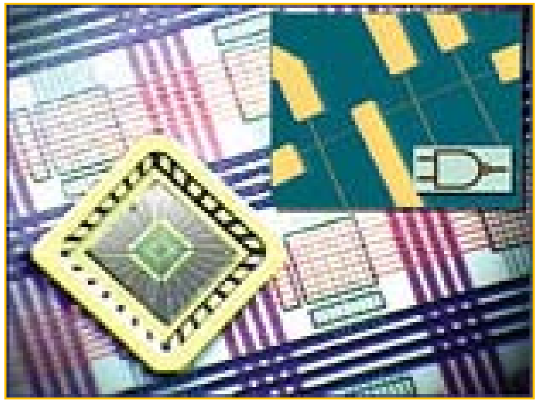
4）尺寸、形貌、结构与物性的可调控性与可组装性；

5）纳米线既可用作基本器件单元，也可用作互联材料；

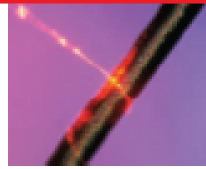
6）纳米线是的构造纳米结构、器件与系统的理想基元。







Nature 441, 18 May 2006



PHYSICS NEWS
Get breaking news on the physical sciences from our website.
www.nature.com/news/channels/physicalsciences.html

stimulates growth and actually boosts overall wealth. At least, that's the conclusion of two of the models — one developed at the University of Cambridge, UK, and the other at the Fondazione Eni Enrico Mattei, a centre for sustainable-development research in Italy. These models suggest that stabilization policies would give an added boost to global GDP of up to 1.7% over 100 years. They assume such climate policies will bring about side benefits, such as increased investment in new technologies.

Ottmar Edenhofer, an economist at the Potsdam Institute for Climate Impact Research in Germany who edited the issue along with Grubb and others, says the new estimates of lost global GDP are significantly lower than previous ones, which put the range at 3–15%. They suggest the price will be a lot lower, agrees Terry Barker, an economist who helped developed the Cambridge model, especially as costs will be spread over 100 years.

The models are likely to influence the next report from the Intergovernmental

物理研究
热点之一

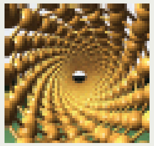
do more, say the authors, particularly in terms of investment in energy technologies, where it lags behind the United States.

But some economists are wary of the results. Jae Edmonds of the Pacific Northwest National Laboratory in Richland, Washington, describes the models as a valuable "intellectual experiment". But he questions the fact that most of the models emphasize learning-by-doing — a process

TOP FIVE IN PHYSICS

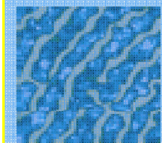
Are you working on the hottest topic in your field? Many scientists may think so, but it has been a tough assertion to prove — until now, that is. A German physicist has devised a way of answering the 'Hot or not?' question for his discipline. If it stands up to scrutiny, it could be used to rate topics across the sciences. In physics, the results show that hotness — measured by a parameter known as *m* — correlates well with the promise of future wealth... and that promise is greatest in nanotechnology.

12.85 Carbon nanotubes



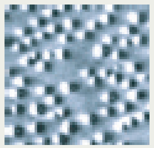
Super-strong materials and blisteringly fast electronic circuits: the potential applications of these tiny carbon tubes, discovered in 1991, are so enticing that everyone is pouring money into the field.

8.75 Nanowires



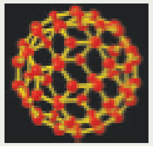
Less well studied than nanotubes, but the possible uses are similar. Nanowires could eventually prove more useful than nanotubes, because their chemistry is easier to tailor and they can be used to create nano-sized lasers.

7.84 Quantum dots



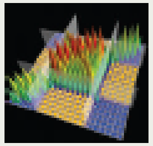
Another nanotechnology with a huge range of potential applications. These tiny specks of semiconductor material, measuring as little as a few nanometres across, have already been used to create dyes for cell biologists and new kinds of laser. Physicists hope they might one day form the basis of a quantum computer.

7.78 Fullerenes



These spheres of carbon atoms are attracting significant research interest. But the latest ranking rewards newness, so the topic may have slipped down the list because it predates nanotubes by around six years. The discovery of fullerenes earned a Nobel prize and spawned studies of numerous potential uses, such as drug delivery agents.

6.82 Giant magnetoresistance



Not a new topic, but still hot because of its economic importance. Modern hard disk drives were made possible by the discovery of giant magnetoresistant materials, which show marked falls in electrical resistance — more than around 5% — when a magnetic field is applied. Researchers are now aiming to make hard disks even more powerful.

Technologies that may change the future of the world

Universal Translation (通用翻译)

Synthetic Biology (人工合成生物学)

Nanowires (纳米线)

Bayesian Machine Learning (贝氏机器学习)

T-Rays (T－射线)

Distributed Storage (分布式存储)

RNAi Therapy (核糖核酸干扰分子疗法)

Power Grid Control (电网控制)

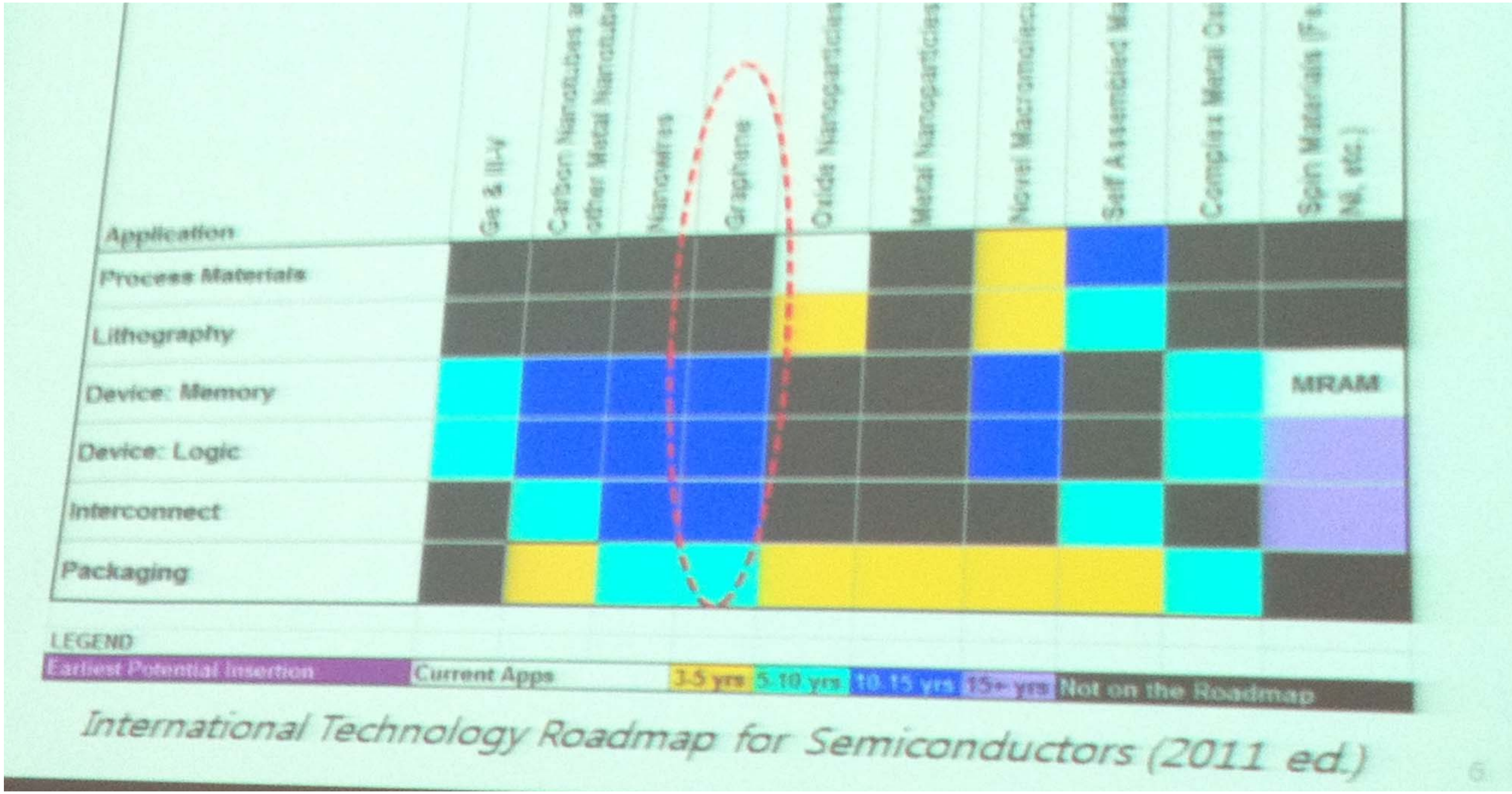
Microfluidic Optical Fibers (微流体光纤)

Personal Genomics (个人基因组学)

Tech. Review, by MIT, USA, 2004

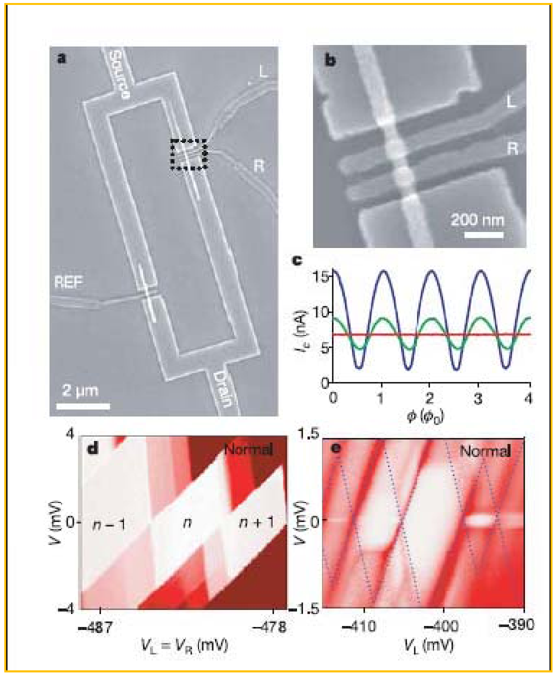
Technologies that may change the future of the world

Outlook for Emerging Materials



Semiconductor Nanowires: Real Quantum Wires

Supercurrent reversal in quantum dots

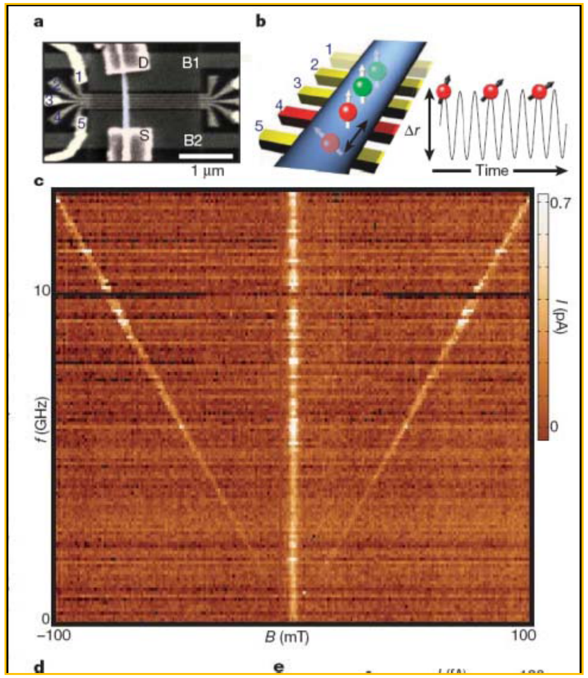


利用纳米线量子点实现超流调控

NATURE 442,667,2006

Leo Kouwenhoven

Spin–orbit qubit in a semiconductor nanowire

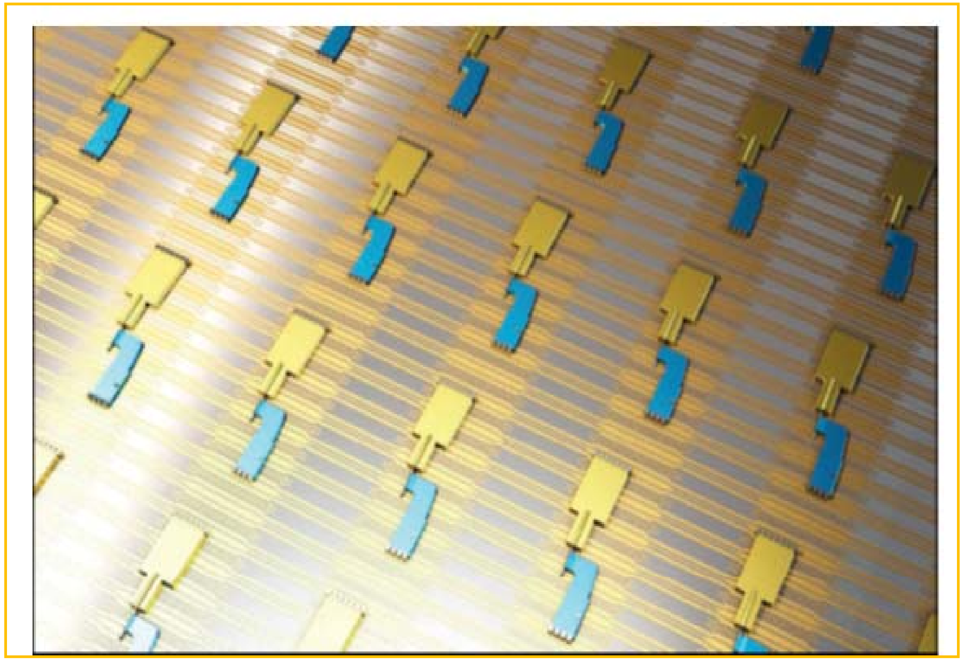


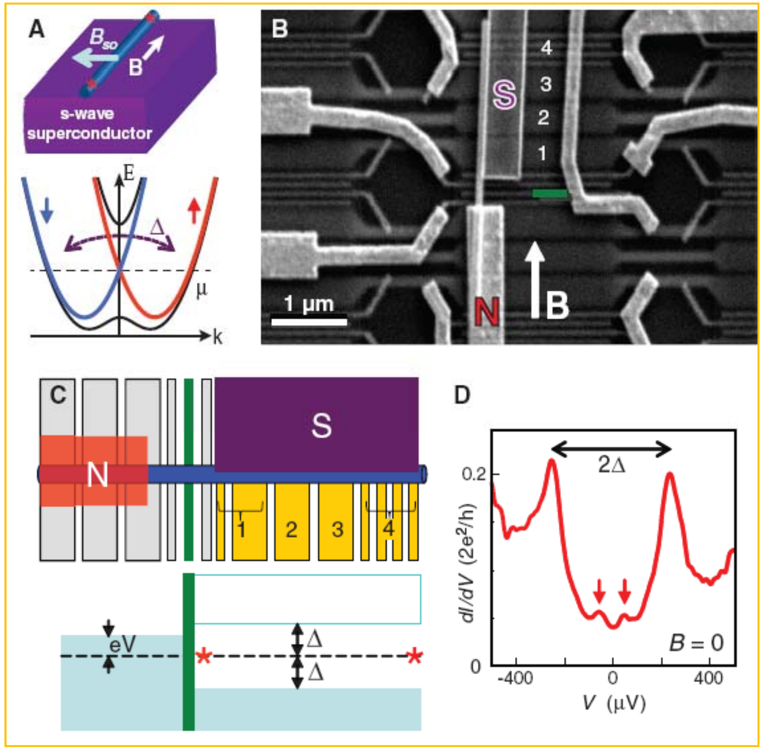
纳米线中的自旋轨道QU 比特器件

Nature 468,1804，2010

Semiconductor Nanowires:
Real Quantum Wires

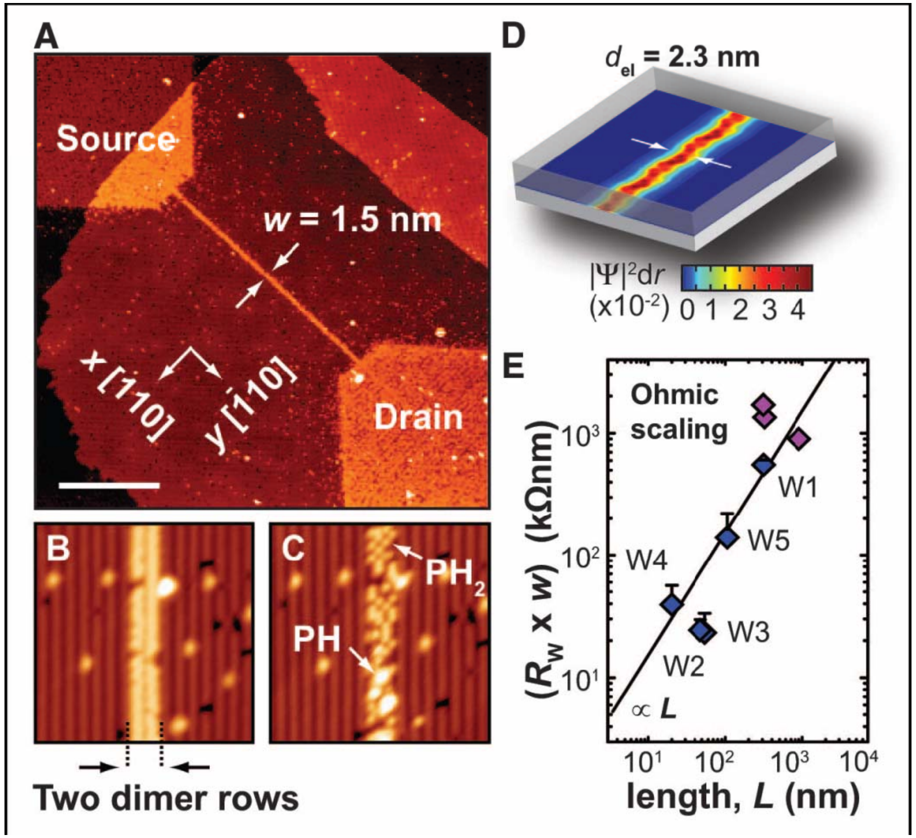
Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

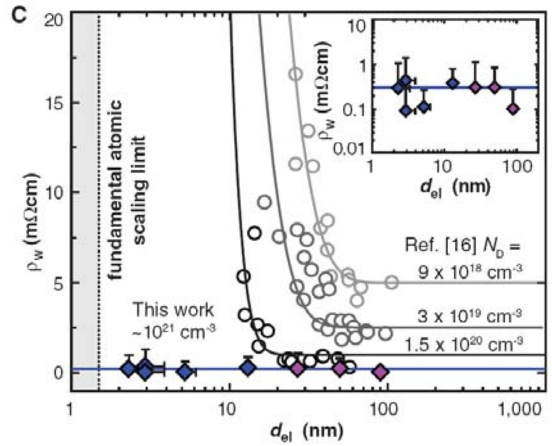


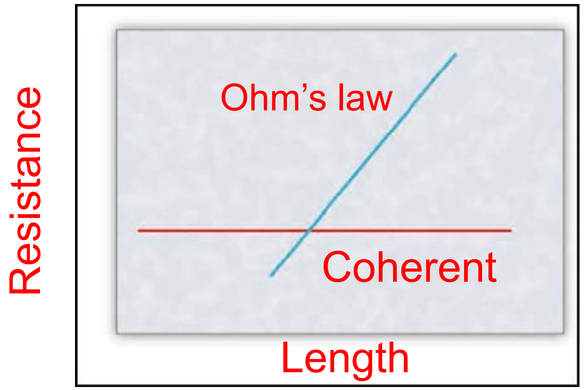


基于InSb纳米线的量子探测器
Majorana费米子存在的证据：Science 336,1003，2012

Ohm's *Law Survives to the* Atomic Scale



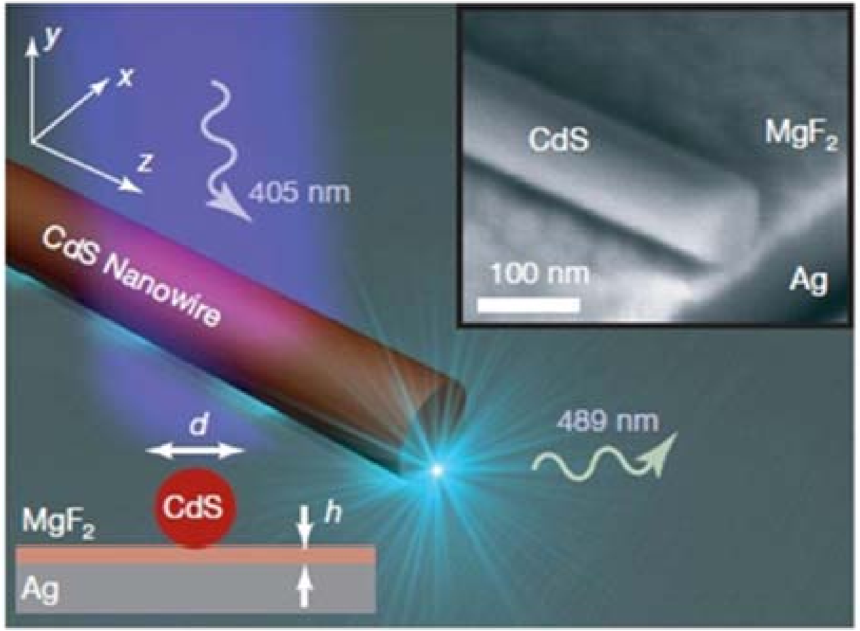


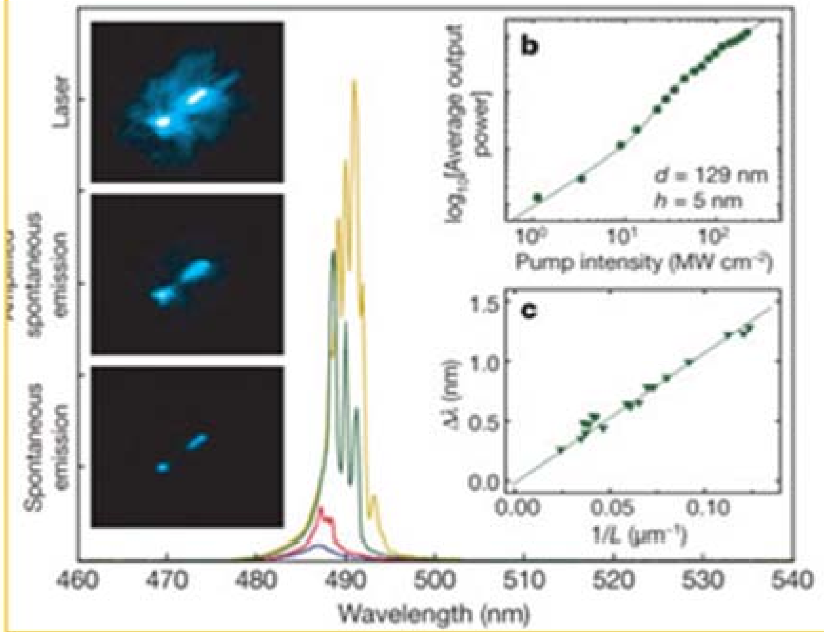


硅纳米线-世界上最细的优良导线

Nano--wires: Big Applications

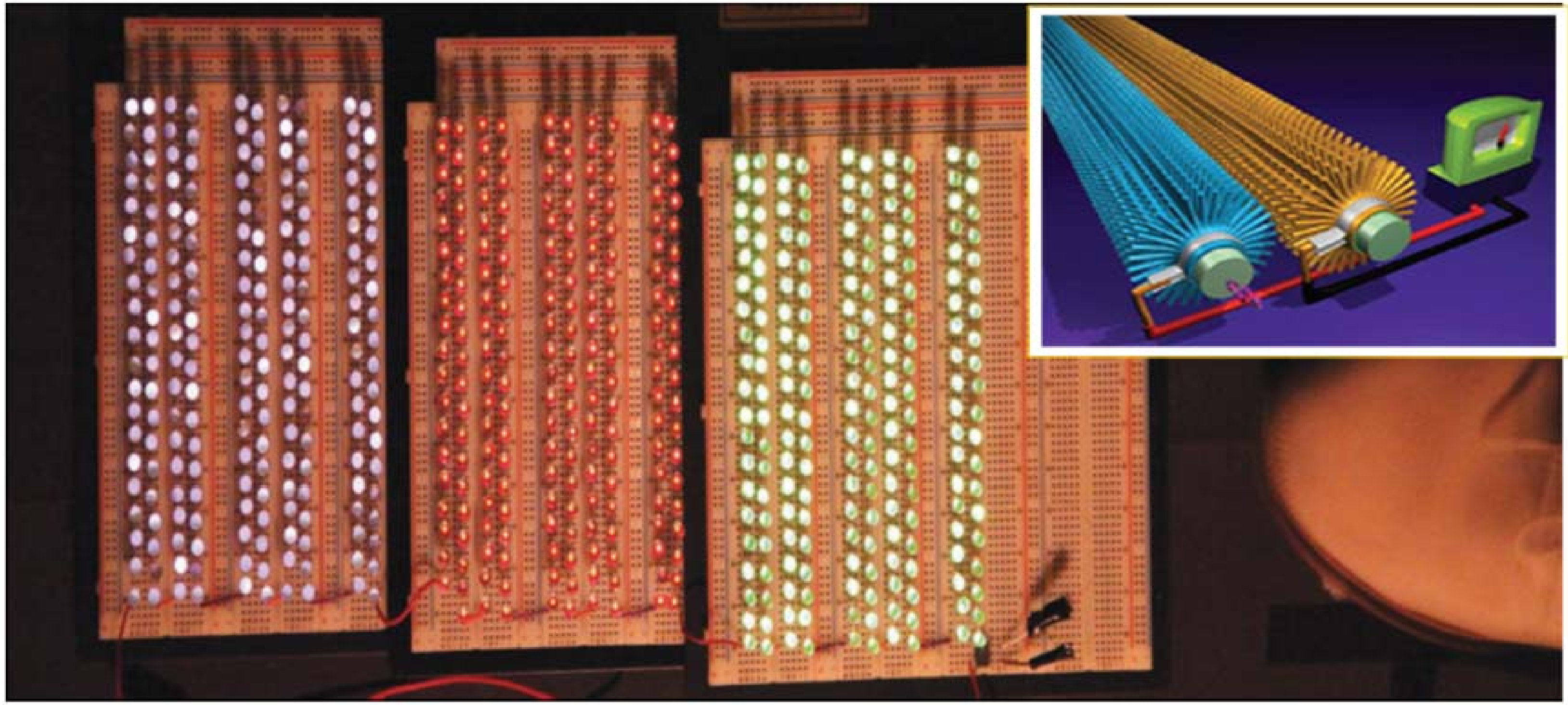
Plasmon lasers at deep subwavelength scale





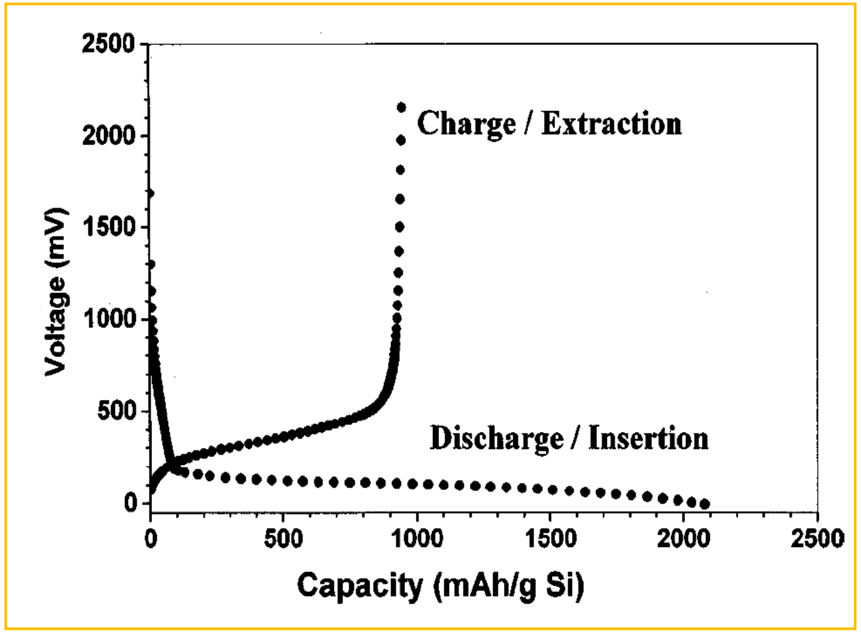
纳米线激光器：Nature 461, 629,2011.

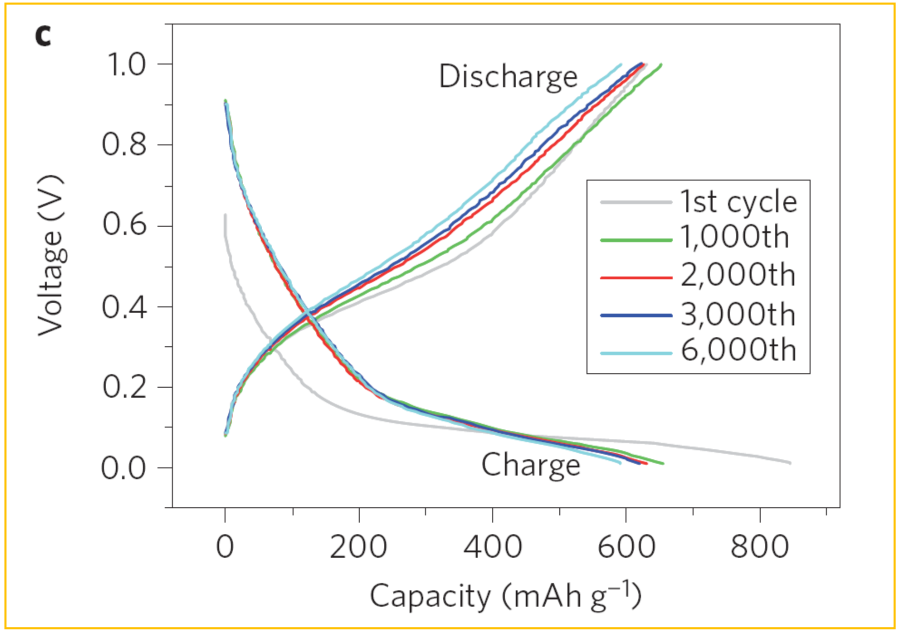
Nano--wires: Big Applications



纳米发电机： Science 2006/Nature 2009/Nano Letters 2012

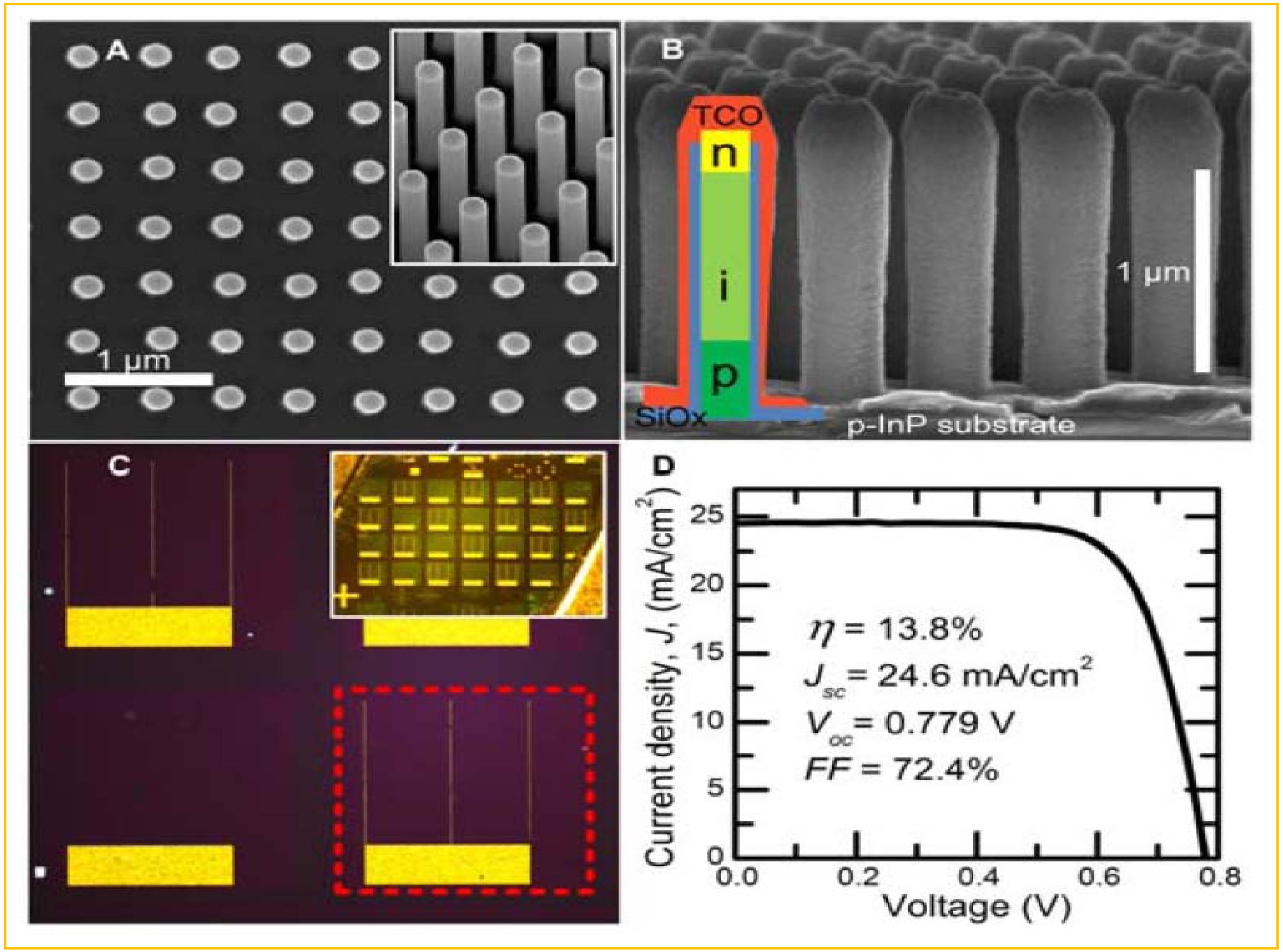
Nano--wires: Big Applications





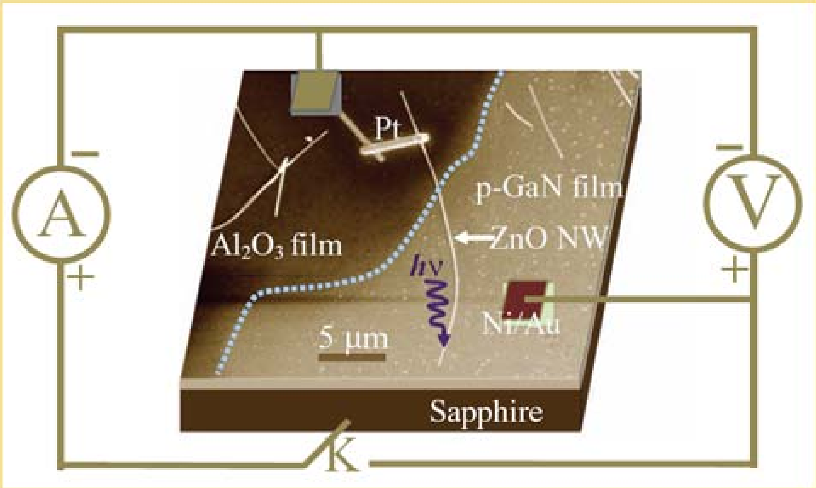
高效锂离子电池 APL：75, 2447,1999; Nature Nano 7: 309-314，2012

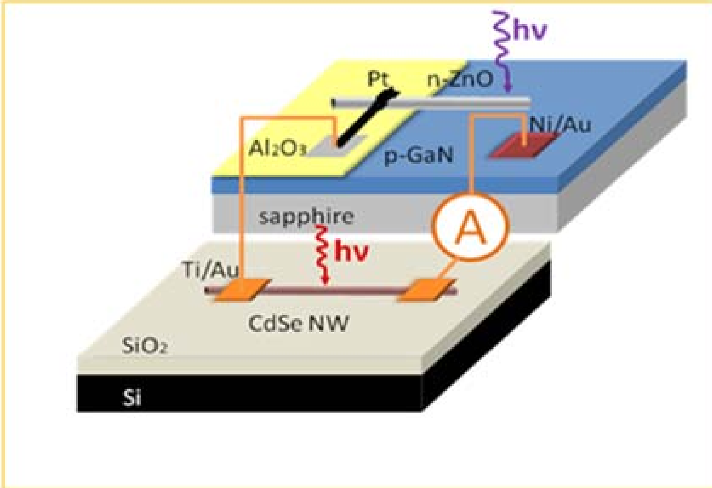
Nano--wires: Big Applications



高效太阳能电池：**Science 335，64，2012**

Nano--wires: Big Applications

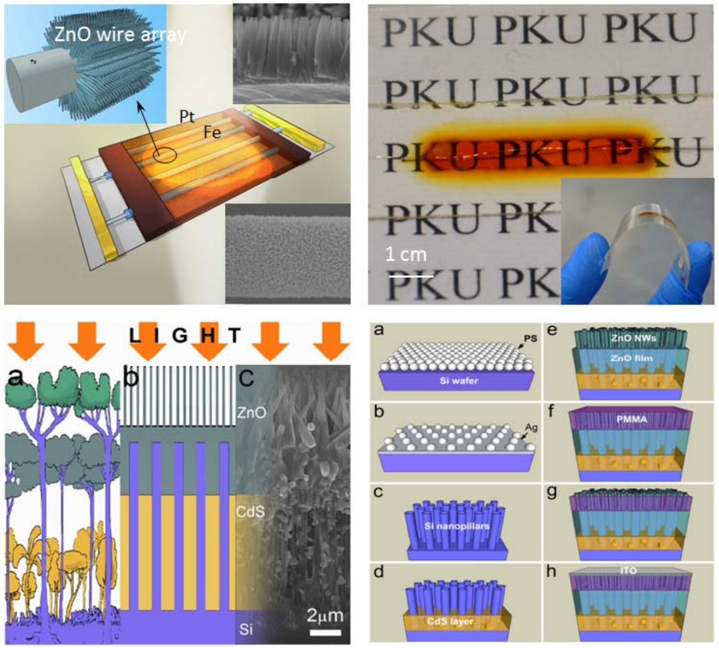


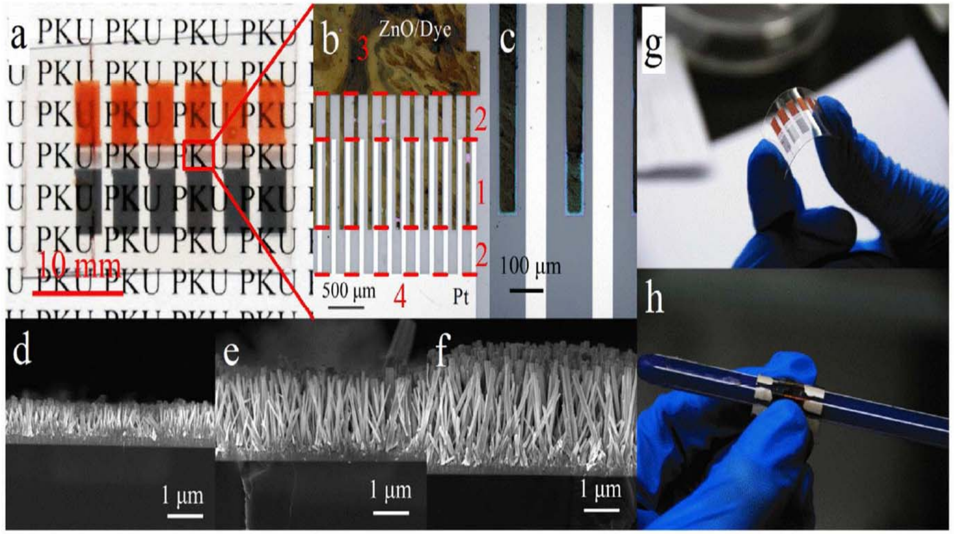


自驱动纳米器件： Advanced Materials 2010; Advanced Materials 2011

别亚青，廖志敏等，

Nano--wires: Big Applications





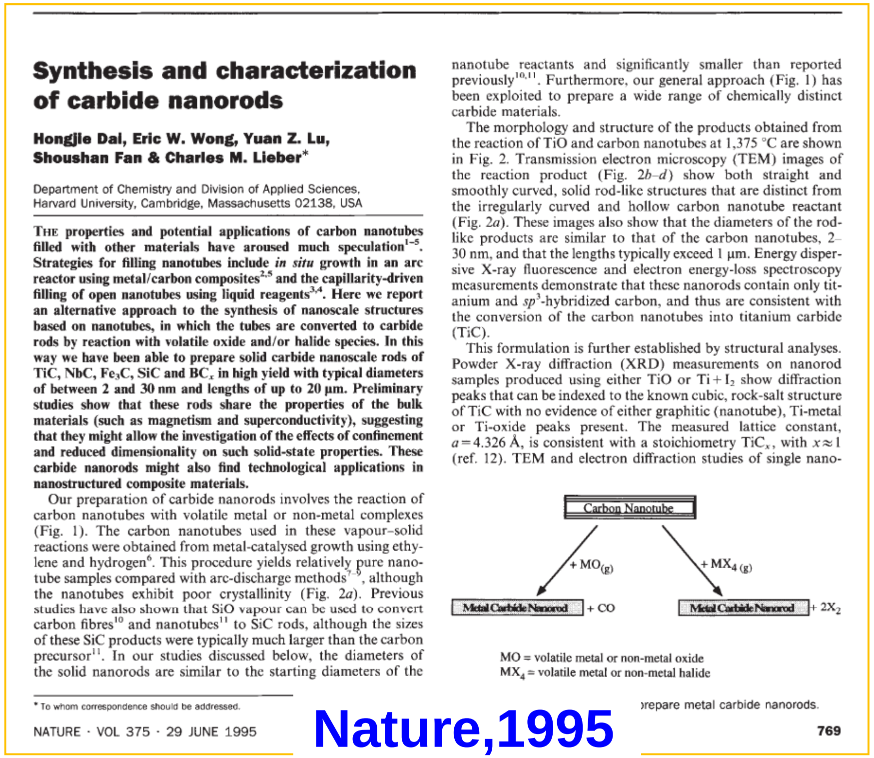
柔性发电/储能：李恒等，**Nano Letters，2013**

柔性太阳能电池：王伟，赵清等，**Advanced Func. Mater. 2012；**

Mass-Synthesis of Nanowires from the bottom

- Leading the mass production of semiconductor nanowires from the bottom;
- Modification of the nanowire properties via doping
- Investigation of the peculiar properties of nanowires
- Explore the possible applications of the nanowires

How to mass-produce nanowires from the bottom?



Synthesis and characterization of carbide nanorods

Hongjie Dai, Eric W. Wong, Yuan Z. Lu, Shoushan Fan & Charles M. Lieber*

Department of Chemistry and Division of Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

The properties and potential applications of carbon nanotubes filled with other materials have aroused much speculation[1–5]. Strategies for filling nanotubes include *in situ* growth in an arc reactor using metal/carbon composites[2,5] and the capillarity-driven filling of open nanotubes using liquid reagents[3,4]. Here we report an alternative approach to the synthesis of nanoscale structures based on nanotubes, in which the tubes are converted to carbide rods by reaction with volatile oxide and/or halide species. In this way we have been able to prepare solid carbide nanoscale rods of TiC, NbC, Fe_3C, SiC and BC_x in high yield with typical diameters of between 2 and 30 nm and lengths of up to 20 μm. Preliminary studies show that these rods share the properties of the bulk materials (such as magnetism and superconductivity), suggesting that they might allow the investigation of the effects of confinement and reduced dimensionality on such solid-state properties. These carbide nanorods might also find technological applications in nanostructured composite materials.

Our preparation of carbide nanorods involves the reaction of carbon nanotubes with volatile metal or non-metal complexes (Fig. 1). The carbon nanotubes used in these vapour–solid reactions were obtained from metal-catalysed growth using ethylene and hydrogen[6]. This procedure yields relatively pure nanotube samples compared with arc-discharge methods[7–9], although the nanotubes exhibit poor crystallinity (Fig. 2*a*). Previous studies have also shown that SiO vapour can be used to convert carbon fibres[10] and nanotubes[11] to SiC rods, although the sizes of these SiC products were typically much larger than the carbon precursor[11]. In our studies discussed below, the diameters of the solid nanorods are similar to the starting diameters of the nanotube reactants and significantly smaller than reported previously[10,11]. Furthermore, our general approach (Fig. 1) has been exploited to prepare a wide range of chemically distinct carbide materials.

The morphology and structure of the products obtained from the reaction of TiO and carbon nanotubes at 1,375 °C are shown in Fig. 2. Transmission electron microscopy (TEM) images of the reaction product (Fig. 2*b–d*) show both straight and smoothly curved, solid rod-like structures that are distinct from the irregularly curved and hollow carbon nanotube reactant (Fig. 2*a*). These images also show that the diameters of the rod-like products are similar to that of the carbon nanotubes, 2–30 nm, and that the lengths typically exceed 1 μm. Energy dispersive X-ray fluorescence and electron energy-loss spectroscopy measurements demonstrate that these nanorods contain only titanium and sp^3-hybridized carbon, and thus are consistent with the conversion of the carbon nanotubes into titanium carbide (TiC).

This formulation is further established by structural analyses. Powder X-ray diffraction (XRD) measurements on nanorod samples produced using either TiO or $Ti + I_2$ show diffraction peaks that can be indexed to the known cubic, rock-salt structure of TiC with no evidence of either graphitic (nanotube), Ti-metal or Ti-oxide peaks present. The measured lattice constant, $a = 4.326$ Å, is consistent with a stoichiometry TiC_x, with $x \approx 1$ (ref. 12). TEM and electron diffraction studies of single nano-

Carbon Nanotube

$+ MO_{(g)}$ → Metal Carbide Nanorod + CO

$+ MX_{4\,(g)}$ → Metal Carbide Nanorod $+ 2X_2$

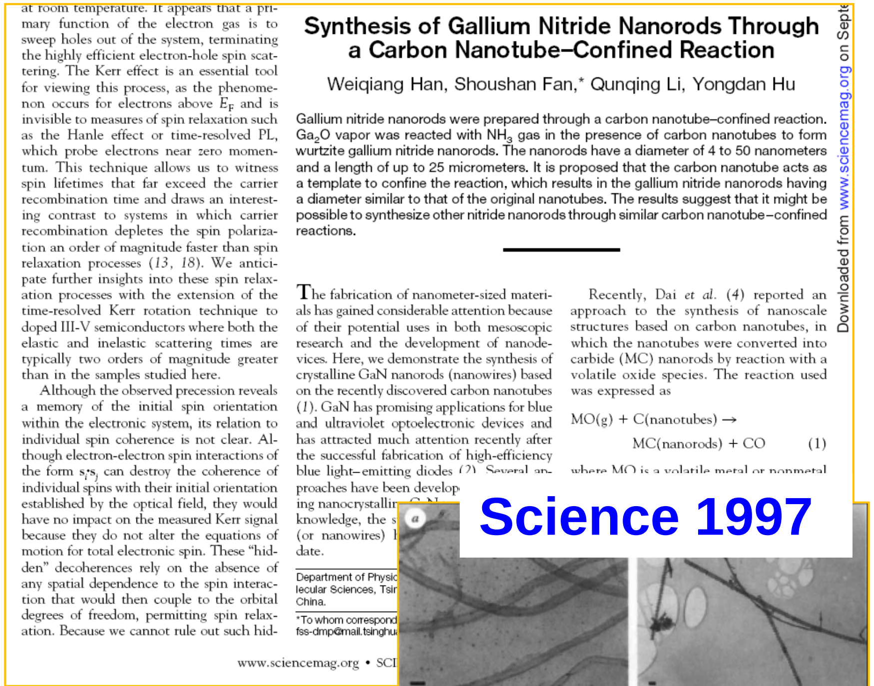
MO = volatile metal or non-metal oxide

MX_4 = volatile metal or non-metal halide

…repare metal carbide nanorods.

* To whom correspondence should be addressed.

Nature,1995



at room temperature. It appears that a primary function of the electron gas is to sweep holes out of the system, terminating the highly efficient electron-hole spin scattering. The Kerr effect is an essential tool for viewing this process, as the phenomenon occurs for electrons above E_F and is invisible to measures of spin relaxation such as the Hanle effect or time-resolved PL, which probe electrons near zero momentum. This technique allows us to witness spin lifetimes that far exceed the carrier recombination time and draws an interesting contrast to systems in which carrier recombination depletes the spin polarization an order of magnitude faster than spin relaxation processes (*13*, *18*). We anticipate further insights into these spin relaxation processes with the extension of the time-resolved Kerr rotation technique to doped III-V semiconductors where both the elastic and inelastic scattering times are typically two orders of magnitude greater than in the samples studied here.

Although the observed precession reveals a memory of the initial spin orientation within the electronic system, its relation to individual spin coherence is not clear. Although electron-electron spin interactions of the form $s_i \cdot s_j$ can destroy the coherence of individual spins with their initial orientation established by the optical field, they would have no impact on the measured Kerr signal because they do not alter the equations of motion for total electronic spin. These "hidden" decoherences rely on the absence of any spatial dependence to the spin interaction that would then couple to the orbital degrees of freedom, permitting spin relaxation. Because we cannot rule out such hid-

Synthesis of Gallium Nitride Nanorods Through a Carbon Nanotube–Confined Reaction

Weiqiang Han, Shoushan Fan,* Qunqing Li, Yongdan Hu

Gallium nitride nanorods were prepared through a carbon nanotube–confined reaction. Ga_2O vapor was reacted with NH_3 gas in the presence of carbon nanotubes to form wurtzite gallium nitride nanorods. The nanorods have a diameter of 4 to 50 nanometers and a length of up to 25 micrometers. It is proposed that the carbon nanotube acts as a template to confine the reaction, which results in the gallium nitride nanorods having a diameter similar to that of the original nanotubes. The results suggest that it might be possible to synthesize other nitride nanorods through similar carbon nanotube–confined reactions.

The fabrication of nanometer-sized materials has gained considerable attention because of their potential uses in both mesoscopic research and the development of nanodevices. Here, we demonstrate the synthesis of crystalline GaN nanorods (nanowires) based on the recently discovered carbon nanotubes (*1*). GaN has promising applications for blue and ultraviolet optoelectronic devices and has attracted much attention recently after the successful fabrication of high-efficiency blue light–emitting diodes (*2*). Several approaches have been develop… ing nanocrystallin… knowledge, the s… (or nanowires) h… date.

Recently, Dai *et al.* (*4*) reported an approach to the synthesis of nanoscale structures based on carbon nanotubes, in which the nanotubes were converted into carbide (MC) nanorods by reaction with a volatile oxide species. The reaction used was expressed as

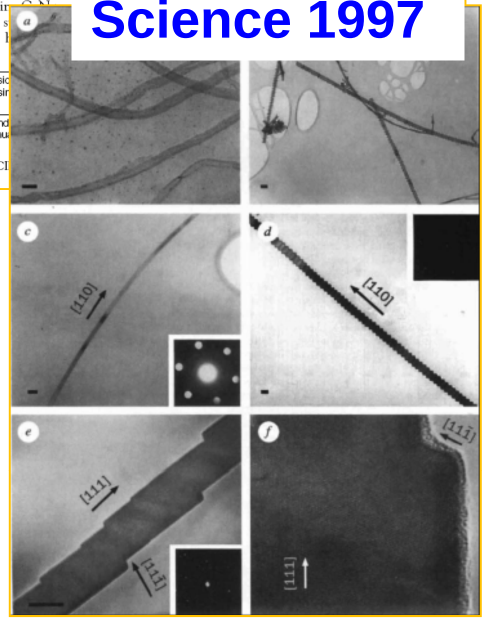
$$MO(g) + C(nanotubes) \rightarrow MC(nanorods) + CO \quad (1)$$

where MO is a volatile metal or nonmetal

Department of Physic… lecular Sciences, Tsin… China.

*To whom correspond… fss-dmp@mail.tsinghu…

Science 1997



Template confined Growth

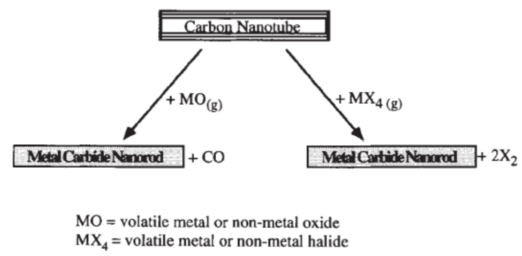


FIG. 1 Reaction scheme used to prepare metal carbide nanorods.

Pioneer Work in Silicon Nanowire Fabrication from the bottom

Pergamon

Solid State Communications, Vol. 105, No. 6, pp. 403–407, 1998

0038–1098/98 $19.00+.00

PII: S0038–1098(97)10143-0

SYNTHESIS OF NANO-SCALE SILICON WIRES BY EXCIMER LASER ABLATION AT HIGH TEMPERATURE

D.P. Yu,[a,b,*] C.S. Lee,[b] I. Bello,[b] X.S. Sun,[b] Y.H. Tang,[b] G.W. Zhou,[c] Z.G. Bai,[a] Z. Zhang[c] and S.Q. Feng[a]

[a]Department of Physics, National Key Laboratory of Mesoscopic Physics, Peking University, 100871 Beijing, China
[b]Department of Physics and Material Science, City University of Hong Kong, Kowloon, Hong Kong
[c]Beijing Laboratory of Electron Microscopy, Academia Sinica, Beijing 100080, China

September 1997; accepted 19 September 1997 by Z.Z. Gan)

elow synthesis of nano-scale silicon wires by using laser
nigh temperature. By this approach we have been able to
on nano wires (SiNW's) with a very high yield, a uniform
tribution and a high purity. The structure, morphology and
nposition of the SiNWs have been characterized by using high
-ray diffraction (XRD), high resolution electron microscopy
well as spectroscopy of energy dispersive X-ray fluorescence
r results should be of great interest to researchers working on
physical phenomena, such as quantum confinement effects
aterials of reduced dimensions and should lead to the
of new applications for nano-scale devices, together with
powerful method for synthesis of similar one-dimensional
nd semi-conducting wire. © 1998 Elsevier Science Ltd

Science AAAS

A Laser Ablation Method for the Synthesis of Crystalline Semiconductor Nanowires
Alfredo M. Morales and Charles M. Lieber
Science **279**, 208 (1998);
DOI: 10.1126/science.279.5348.208

A Laser Ablation Method for the Synthesis of Crystalline Semiconductor Nanowires

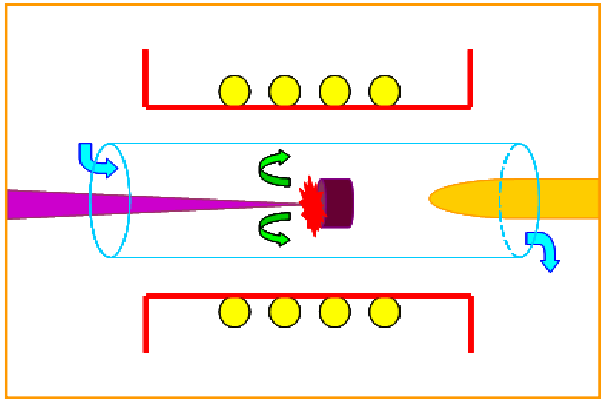
M. Morales and Charles M. Lieber*

er ablation cluster formation and vapor-liquid-solid (VLS) growth
synthesis of semiconductor nanowires. In this process, laser
epare nanometer-diameter catalyst clusters that define the size
LS growth. This approach was used to prepare bulk quantities
silicon and germanium nanowires with diameters of 6 to 20 and
ectively, and lengths ranging from 1 to 30 micrometers. Studies
t conditions and catalyst materials confirmed the central details
n and suggest that well-established phase diagrams can be used
alyst materials and growth conditions for the preparation of

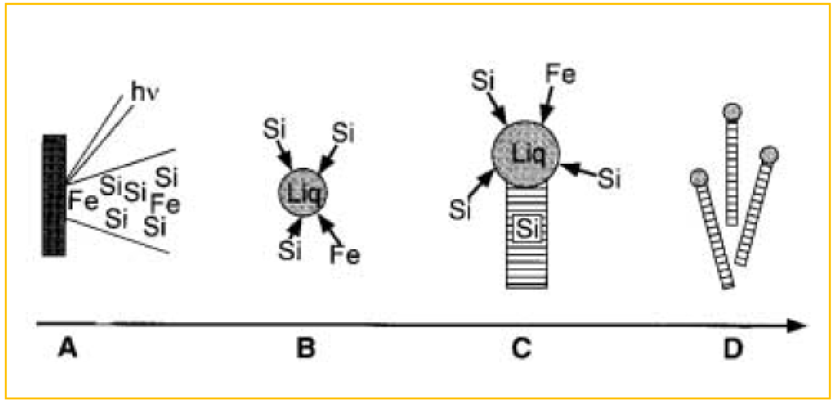
Yu DP, et al., Solid State Communications 1998, 105, 403.

Morales et al., Science 1998,279, 208.

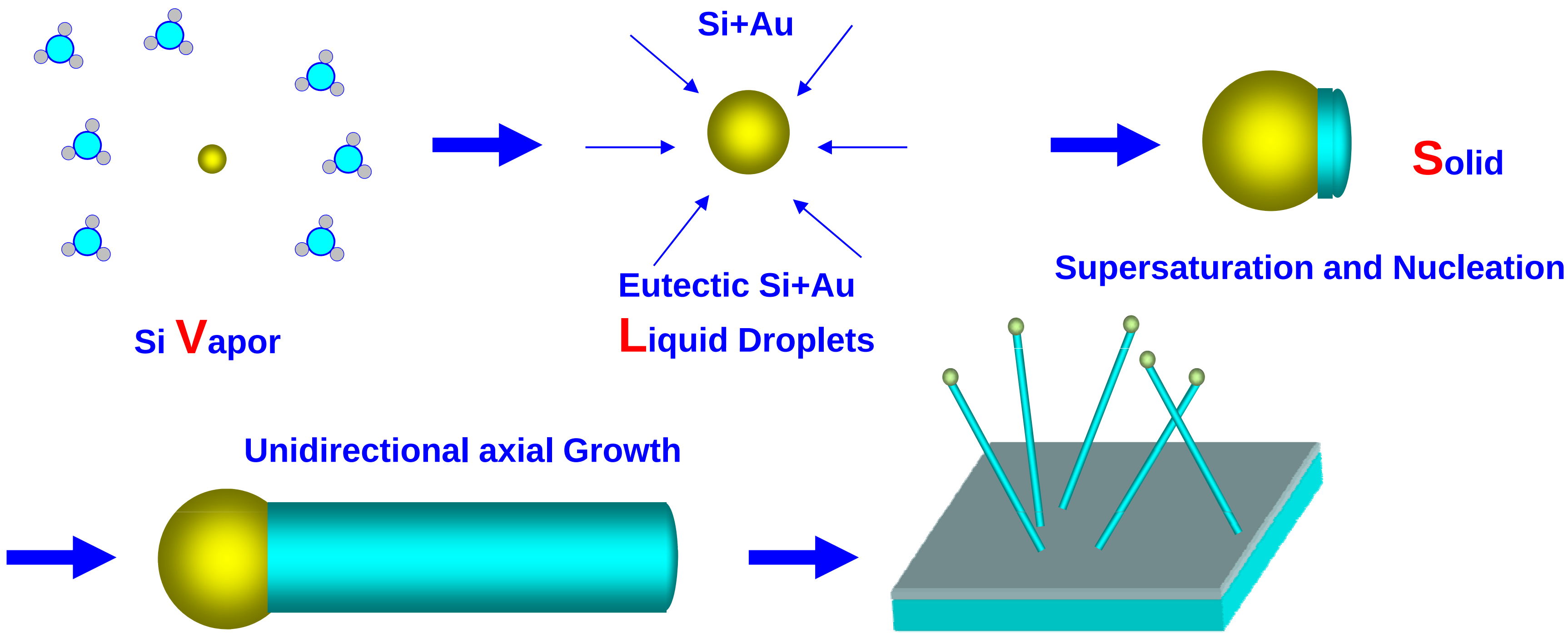
VLS Directed Axial Growth of Silicon Nanowires



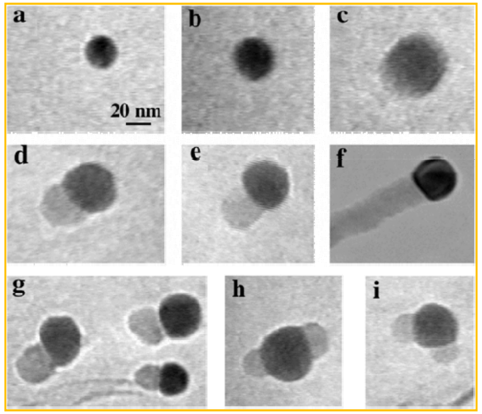
Laser Ablation Setup



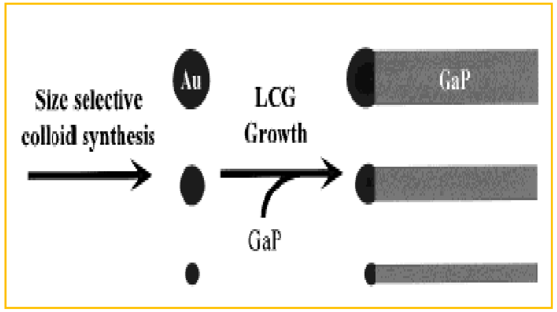
Growth Process



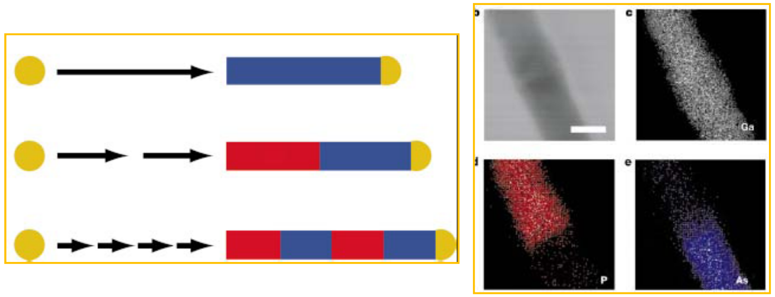
Merit of the VLS growth



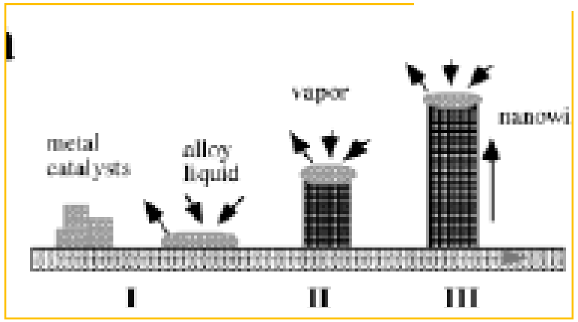
In Situ TEM Proved:pd Yang Jacs 2001, 123, 3165

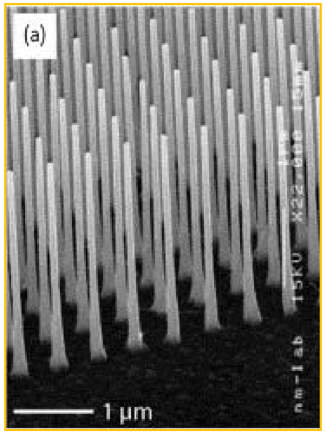


J. Am. Chem. Soc. 2000, 122, 8801

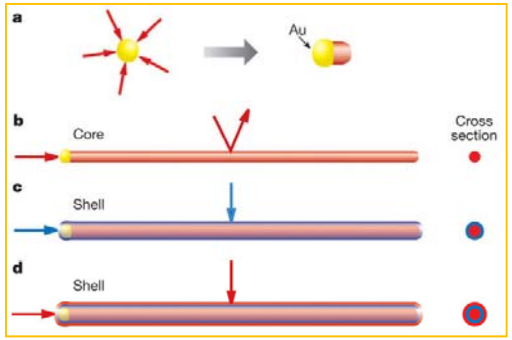


GaAs/GaP Nanowire Superlattice: Nature 415 , (2002)617, C.M. Lieber.

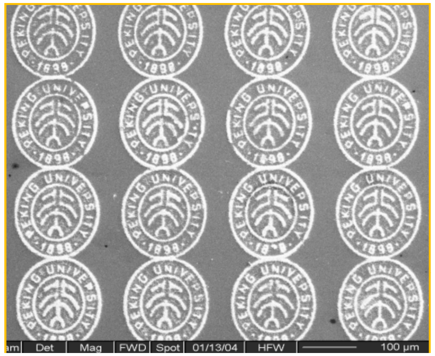




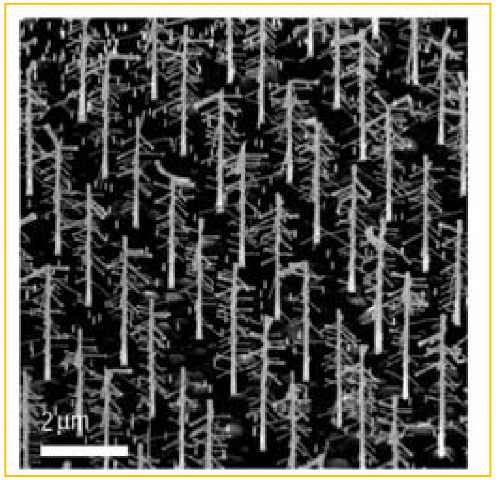
InAs Nanowhisker arrays: Nano Letters, 2002, 2,87, L. Samuelson



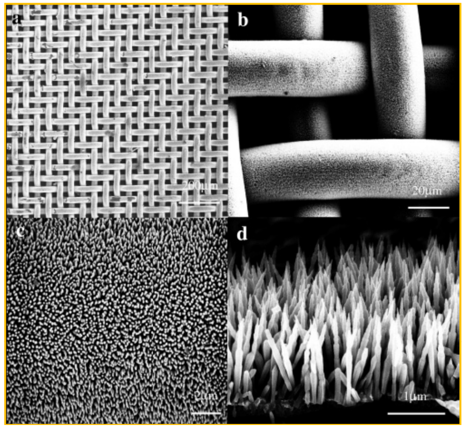
Ge/Si Core/Shell Nanocables Nature 2004,430,61, J. Xiang



Patterned Growth of nanowire arrays D.P. Yu et al

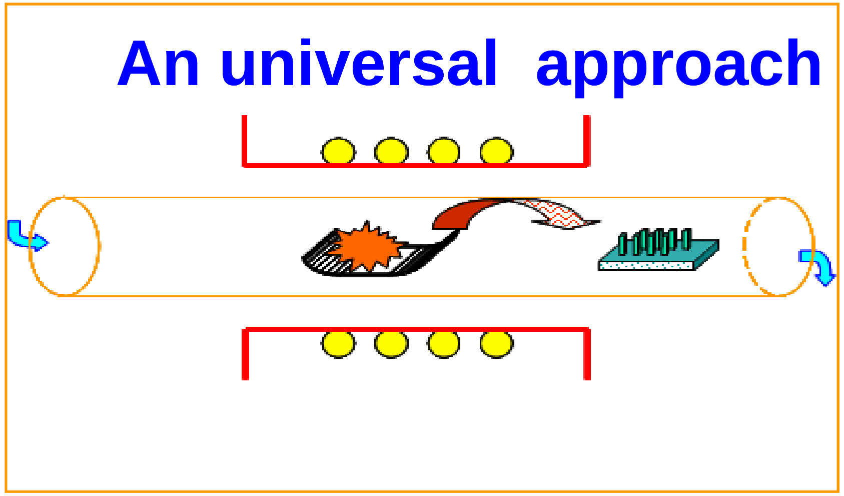


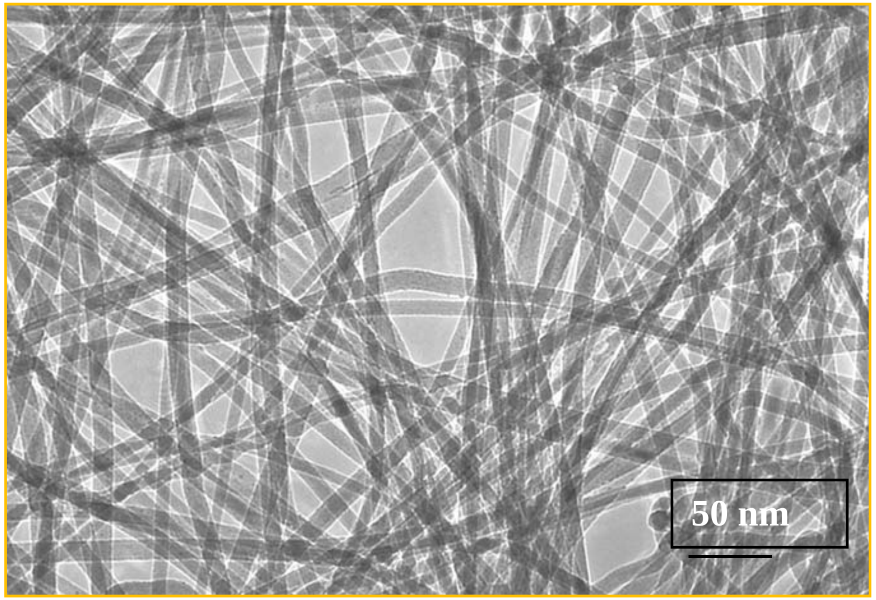
Nanotrees: Nature Materials 3,380,2004 ,L. Samuelson



Nanowire Arrays On Metal Grid: X..Y. Xu et al., JPCB 2005, 109, 1699

Facile Fabrication SiNWs via Physical Vapor Deposition –Lost cost then popular





Featured Articles

Si: Applied Physics Letters 72，1998

Si: Applied Physics Letters 72, 1835:1998

Applied Physics Letters 73，3396，1998

Applied Physics Letters 73，3396，1998

Si: Physical Review B 59，1645，1999

Si: Physical Review B 61， 16827，2000

Physical Review B 59，R2498，1999

Si: Chemical Physics Letters 323，224，2000

Advanced Materials 15，419，2003

Breakthrough in Oxide Nanowires

APPLIED PHYSICS LETTERS VOLUME 73, NUMBER 21

Amorphous silica nanowires: Intensive blue light emitters

D. P. Yu,[a] Q. L. Hang, Y. Ding, H. Z. Zhang, Z. G. Bai, J. J. Wang, Y. H. Zou, W. Qian, G. C. Xiong, and S. Q. Feng
Department of Physics, National Key Laboratory of Mesoscopic Physics, Peking University, and Electron Microscopy Laboratory, Peking University, Beijing 100871, People's Republic of China

(Received 12 June 1998; accepted for publication 25 September 1998)

SiO_2 Nanowires, 1998

PERGAMON

Ga_2O_3 Nanowires, 1999

Solid State Communications 109 (1999) 677–682

solid state communications

Ga_2O_3 nanowires prepared by physical evaporation

H.Z. Zhang, Y.C. Kong, Y.Z. Wang, X. Du, Z.G. Bai, J.J. Wang, D.P. Yu*, Y. Ding, Q.L. Hang, S.Q. Feng
Department of Physics, National Key Laboratory of Mesoscopic Physics, and Electron Microscopy Laboratory, Peking University, Beijing 100871, People's Republic of China

Received 15 November 1998; accepted 16 December 1998 by Z. Gan

ELSEVIER

9 April 1999

GeO_2 Nanowires, 1999

Chemical Physics Letters 303 (1999) 311–314

CHEMICAL PHYSICS LETTERS

Nano-scale GeO_2 wires synthesized by physical evaporation

Z.G. Bai, D.P. Yu *, H.Z. Zhang, Y. Ding, Y.P. Wang, X.Z. Gai, Q.L. Hang, G.C. Xiong, S.Q. Feng
Department of Physics, National Key Laboratory of Mesoscopic Physics, and Electron Microscopy Laboratory, Peking University, Beijing 100871, China

Received 16 July 1998; in final form 7 January 1999

Featured Articles

MgO: Nanostructured Materials 15， 1442，1997

SiO_2: Applied Physics Letters 73， 3076，1998；

ZnO： Applied Physics Letters 78 407，2001

Ga_2O_3: Solid State Commus. 109，677，1999；

GeO_2: Chemical Physics Letters 303，311，1999

Applied Physics Letters 72，1966，1998

Applied Physics Letters 72,1966,1998

Applied Physics Letters 83，4631，2003

Advanced Materials 15，1442，2003

Nano Letters 7，323，2007

Nano Letters 8，3640，2008

J. Amer. Chemical Society 123，9904，2001

J. Amer. Chemical Society 125，10794，2003

J. Amer. Chemical Society 124，13370，2002

Breakthrough in ZnO Nanowires

Ultraviolet-emitting ZnO nanowires synthesized by a physical vapor deposition approach

Y. C. Kong,[a)] D. P. Yu,[b)] B. Zhang, W. Fang, and S. Q. Feng
Department of Physics, Mesoscopic Physics National Laboratory, and Electron Microscopy Laboratory, Peking University, Beijing 100871, China

(Received 26 April 2000; accepted for publication 19 November 2000)

Thermal Evaporation of Zinc Powders at 1100℃;
times cited:799 .

Applied Physics Letters 78, 407, January 2001

Catalytic Growth of Zinc Oxide Nanowires by Vapor Transport**

By *Michael H. Huang*, *Yiying Wu*, *Henning Feick*, *Ngan Tran*, *Eicke Weber*, and *Peidong Yang**

Thermal evaporation of ZnO powder + graphite at 925 ℃.
times cited:1631 .

Advanced Materials 13, 113, January 2001

Nanobelts of Semiconducting Oxides

Zheng Wei Pan,[1] Zu Rong Dai,[1] Zhong Lin Wang[1,2]*

Thermal evaporation of ZnO powders at 1400 ℃.
times cited:3783.

Science 291, 1947, March 2001

101 papers contributed to the field

Pioneers in Nanowires Research

- Leading the mass production of semiconductor nanowires from the bottom;
- Modification of the nanowire properties via doping
- Investigation of the peculiar properties of nanowires
- Explore the possible applications of the nanowires

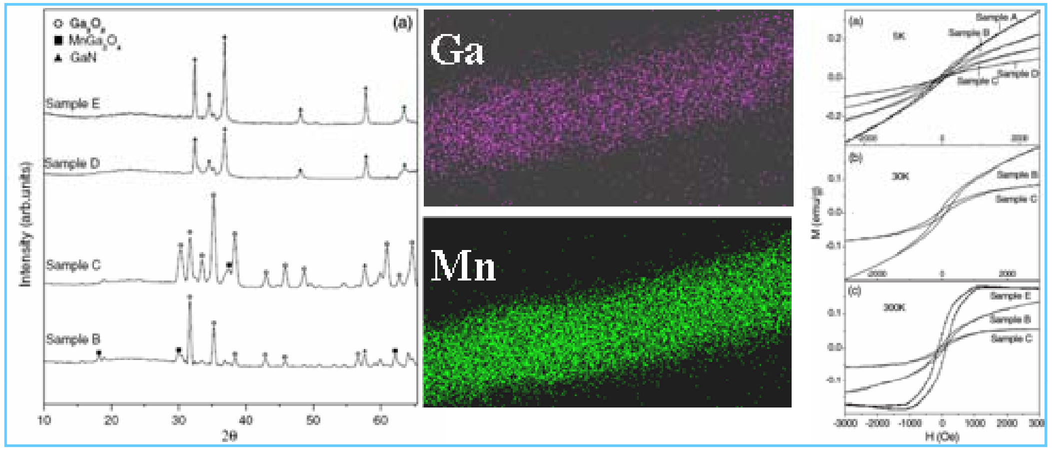
Ferromagnetic Ordering via Transition Metal doping in Semiconductor Nanowires-DMS

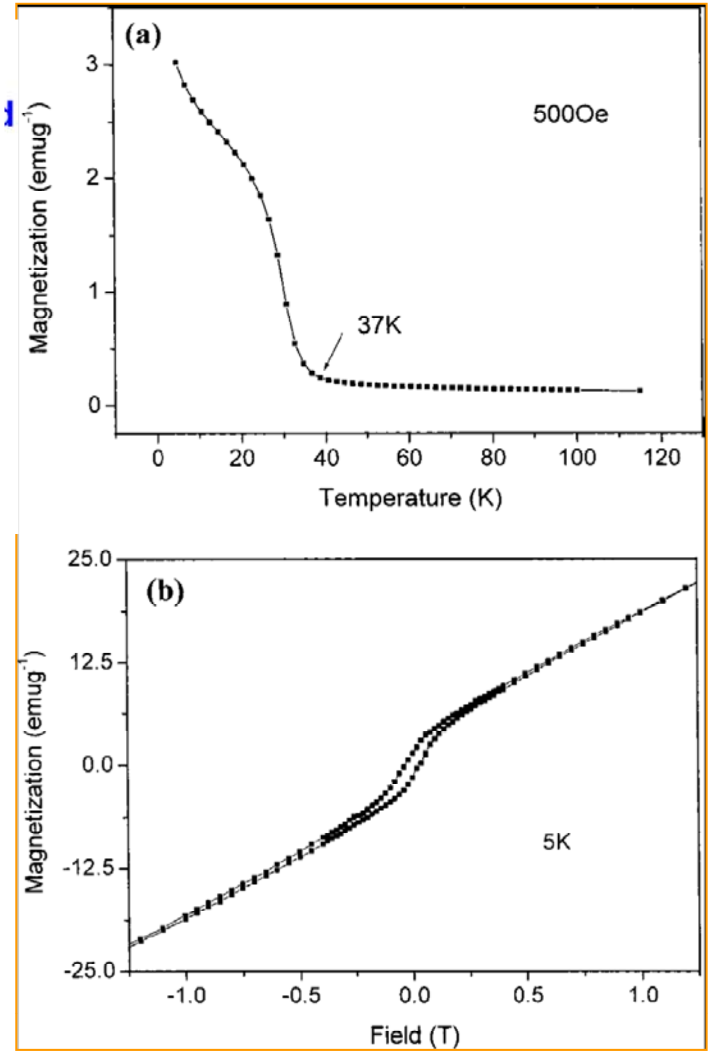
PHYSICAL REVIEW B **69**, 075304 (2004)

Luminescence emission originating from nitrogen doping of β-Ga_2O_3 nanowires

Y. P. Song,[1] H. Z. Zhang,[1] C. Lin,[2] Y. W. Zhu,[1] G. H. Li,[3] F. H. Yang,[3] and D. P. Yu[1,*]
[1]*School of Physics, National Kay Laboratory of Mesoscopic Physics, and Electron Microscopy Laboratory, Peking University, Beijing 100871, People's Republic of China*
[2]*Spex Fluorescence Jobin Yvon, Inc., Edison, New Jersey 08820, USA*
[3]*Semiconductor Institute, Chinese Academic of Sciences, Beijing 100083, People's Republic of China*
(Received 9 September 2003; published 10 February 2004)

Nitrogen-doped β-Ga_2O_3 nanowires (GaO NWs) were prepared by annealing the as-grown nanowires in an ammonia atmosphere. The optical properties of the nitrogen-doped GaO NWs were studied by measurements of the photoluminescence and phosphorescence decay at the temperature range between 10 and 300 K. The experimental results revealed that nitrogen doping in GaO NWs induced a novel intensive red-light emission around 1.67 eV, with a characteristic decay time around 136 μs at 77 K, much shorter than that of the blue emission (a decay time of 457 μs). The time decay and temperature-dependent luminescence spectra were calculated theoretically based on a donor-acceptor pair model, which is in excellent agreement with the experimental data. This result suggests that the observed novel red-light emission originates from the recombination of an electron trapped on a donor due to oxygen vacancies and a hole trapped on an acceptor due to nitrogen doping.





Appl. Phys. Letters 83, 4020, 2003

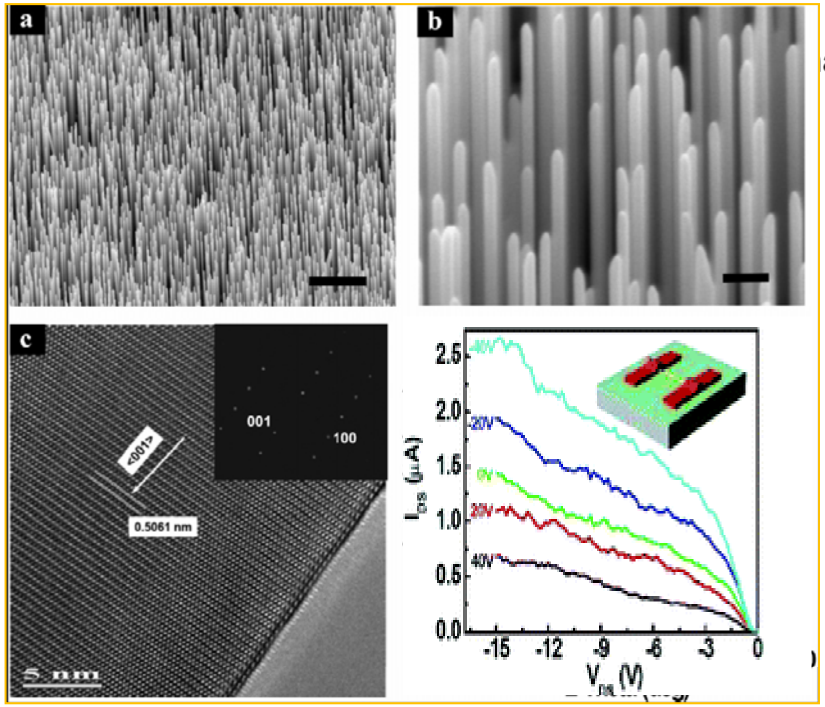
P-ZnO Nanowire Doping

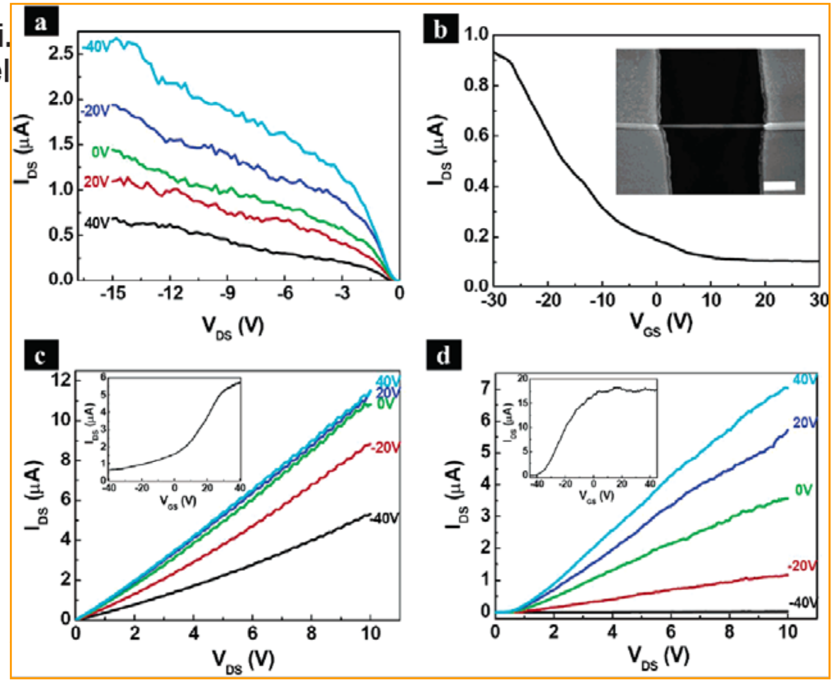
Bin Xiang[1], Pengwei Wang[2], Xingzheng Zhang[2], Shadi Dayeh[1], David Aplin[1], Cesare Soci[1], Dapeng Yu[2], and Deli Wang[1] --[1]UCSD； [2]PKU

NANO LETTERS

2007
Vol. 7, No. 2
323−328

Rational Synthesis of p-Type Zinc Oxide Nanowire Arrays Using Simple Chemical Vapor Deposition





ZnO Nanowire p-n Junction

Electrical and Photoresponse Properties of an Intramolecular p-n Homojunction in Single Phosphorus-Doped ZnO Nanowires

Ping-Jian Li,† Zhi-Min Liao,† Xin-Zheng Zhang,† Xue-Jin Zhang,† Hui-Chao Zhu,† Jing-Yun Gao,† K. Laurent,‡ Y. Leprince-Wang,‡ N. Wang,§ and Da-Peng Yu*,†

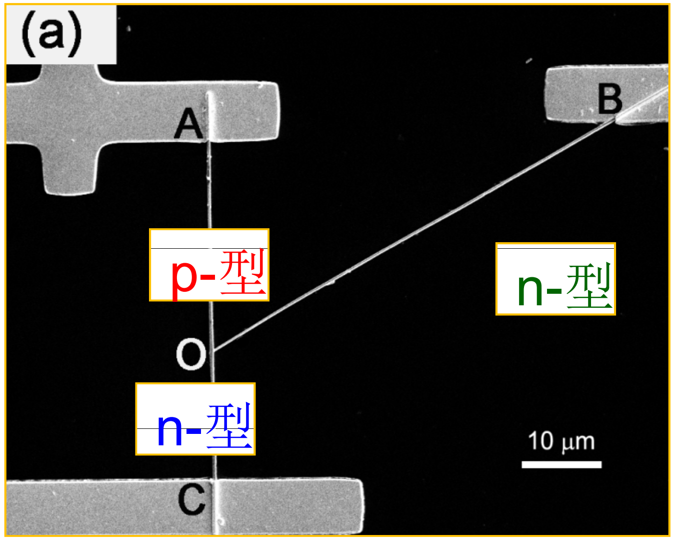
State Key Laboratory for Mesoscopic Physics, and Electron Microscopy Laboratory, School of Physics, Peking University, Beijing 100871, Peoples's Republic of China, Laboratoire de Physique des Materiaux Divises et Interfaces (LPMDI), CNRS-UMR 8108, Universite Paris-Est, 77454 Marne la Vallee Cedex 2, France, and Physics Department, Hong Kong University of Science and Technology, Hong Kong

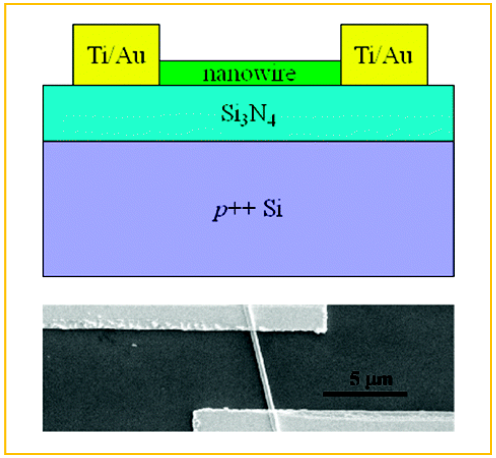
Received November 14, 2008; Revised Manuscript Received May 21, 2009

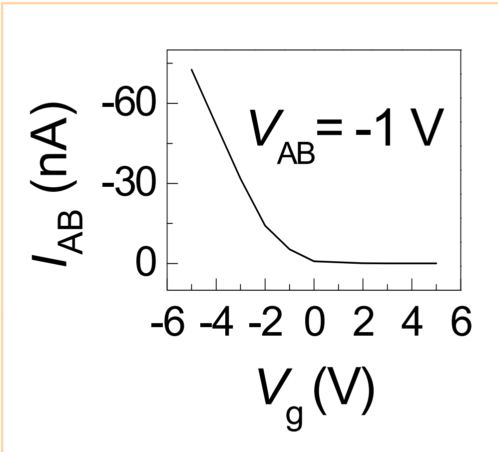
Nano Letters 9，2513，2009

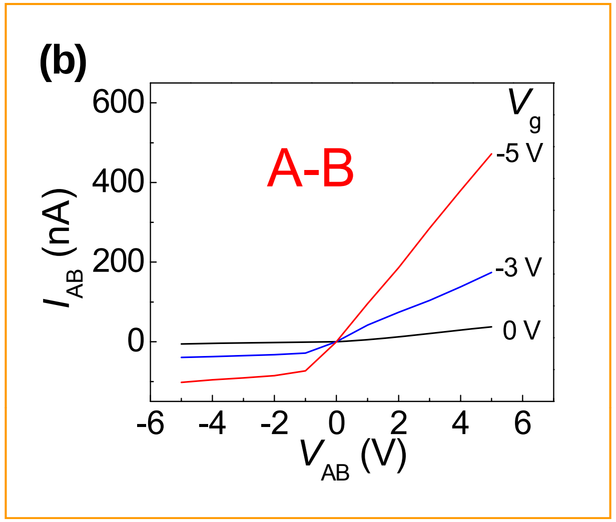
ABSTRACT

The single-crystal n-type and p-type ZnO nanowires (NWs) were synthesized via a chemical vapor deposition method, where phosphorus pentoxide was used as the dopant source. The electrical and photoluminescence studies reveal that phosphorus-doped ZnO NWs (ZnO:P NWs) can be changed from n-type to p-type with increasing P concentration. Furthermore, we report for the first time the formation of an intramolecular p-n homojunction in a single ZnO:P NW. The p-n junction diode has a high on/off current ratio of 2.5×10^3 and a low forward turn-on voltage of ~1.37 V. Finally, the photoresponse properties of the diode were investigated under UV (325 nm) excitation in air at room temperature. The high photocurrent/dark current ratio (3.2×10^4) reveals that the diode has a potential as extreme sensitive UV photodetectors.









P-ZnO Nanowire Doping

Featured Articles

1. Rational synthesis of p-type zinc oxide nanowire arrays using simple chemical vapor deposition, Nano Letters 7: 323,2007;
2. Electrical and Photoresponse Properties of an Intramolecular p-n Homojunction in Single Phosphorus-Doped ZnO Nanowires, Nano Letters 9: 2813, 2009;
3. First-principles study of the formation mechanisms of nitrogen molecule in annealed ZnO; Physics Letters A 374: 34: 3546, 2010;
4. A Novel Way for Synthesizing Phosphorus-Doped Zno Nanowires, Nanoscale Research Letters 6 : 45, 2011;
5. Compensation mechanism in N-doped ZnO nanowires, NANOTECHNOLOGY 21: 245703, 2011.

Pioneers in Nanowires Research

- Leading the mass production of semiconductor nanowires from the bottom;
- Modification of the nanowire properties via doping
- Investigation of the peculiar properties of nanowires
- Explore the possible applications of the nanowires

Property Exploration of the nanowires

PRL **104,** 146601 (2010) PHYSICAL REVIEW LETTERS week ending 9 APRIL 2010

Evidence for Thermal Spin-Transfer Torque

Haiming Yu,[1,2] S. Granville,[1] D. P. Yu,[2] and J.-Ph. Ansermet[1]

[1]*Ecole Polytechnique Fédérale de Lausanne, IPMC, Station 3, CH-1015 Lausanne-EPFL, Switzerland*

[2]*State Key Laboratory for Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, People's Republic of China*

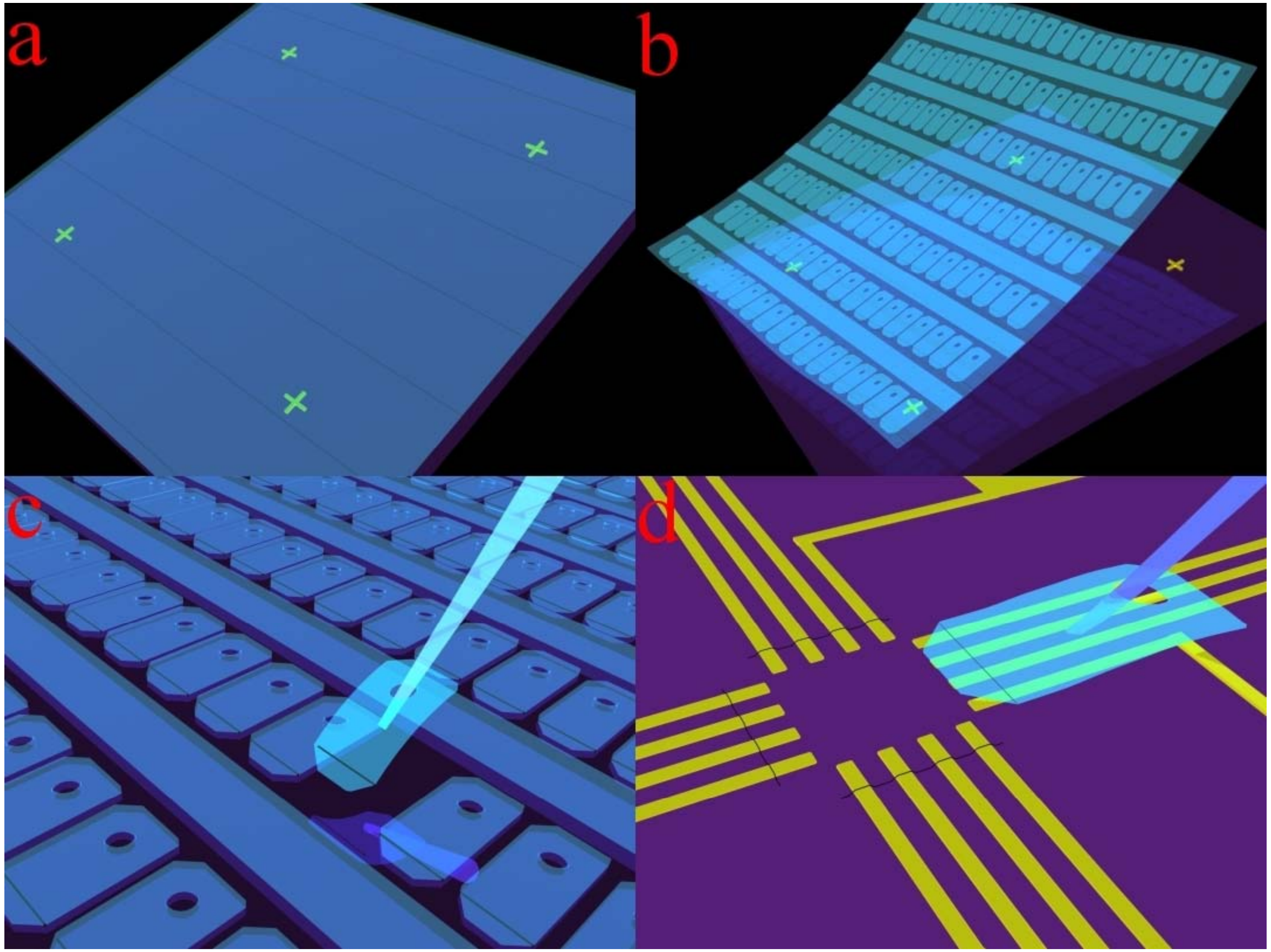
(Received 1 December 2009; published 9 April 2010)

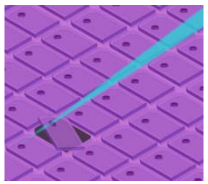
Large heat currents are obtained in Co/Cu/Co spin valves positioned at the middle of Cu nanowires. The second harmonic voltage response to an applied current is used to investigate the effect of the heat current on the switching of the spin valves. Both the switching field and the magnitude of the voltage response are found to be dependent on the heat current. These effects are evidence for a thermal spin-transfer torque acting on the magnetization and are accounted for by a thermodynamic model in which heat, charge and spin currents are linked by Onsager reciprocity relations.

DOI: 10.1103/PhysRevLett.104.146601 PACS numbers: 72.15.Jf, 75.60.Jk, 85.75.−d

[S0163-1829(99)51604-4]

Micro-Stamp Transfer Technique

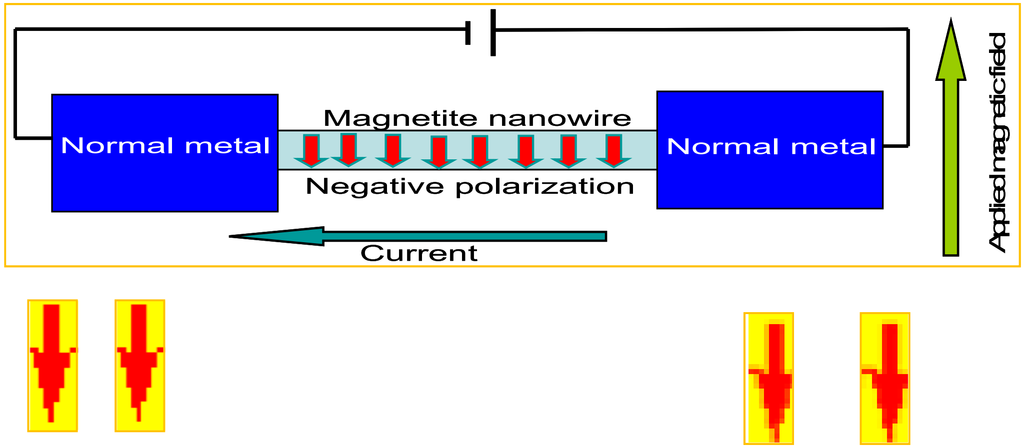




中国专利：ZL 2009 1 0236921.7

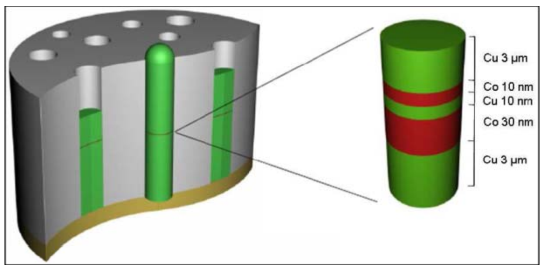
Property Exploration of the nanowires

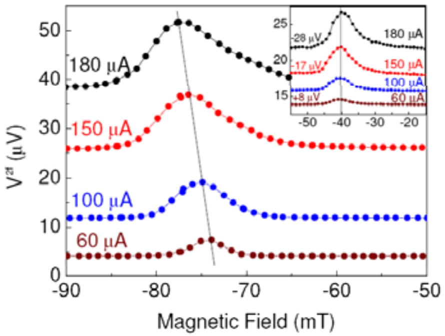
Nanowire Spin Filter, by 廖志敏 et al.



Nano Letters 8，3640，2008

Spin Transfer Torque Nanowire Spin Valve： 于海明 et al.





Physical Review Letters 105， 127402，2010

Featured Articles

Physical Review B 59，1645，1999

Physical Review B B 61， 16827，2000

Physical Review B 59，R2498，1999

Physical Review B 73，235409，2006

Physical Review B 69，075304 ，2004

Physical Review B 65，245403，2002

Physical Review B 71， 235417，2005.

Physical Review B 70,245412,2004

Physical Review Letters 105， 127402，2010

Applied Physics Letters 72，1966，1998

Applied Physics Letters 83，1689，2003

Nano Letters 8，3640，2008

Nano Letters 11，4601，2011

J. Amer. Chem. Soc. 128，5114，2006

J. Amer. Chem. Soc. 128，5114，2006

J. Amer Chem. Soc. 131，2436，2010

Pioneers in Nanowires Research

- Leading the mass production of semiconductor nanowires from the bottom;
- Modification of the nanowire properties via doping
- Investigation of the peculiar properties of nanowires
- Explore the possible applications of the nanowires.

Silicon nanowires as the anode materials in lithium battery

We are the 1st to address the issue

ELSEVIER

Solid State Ionics 135 (2000) 181–191

SOLID STATE IONICS

www.elsevier.com/locate/ssi

The crystal structural evolution of nano-Si anode caused by lithium insertion and extraction at room temperature

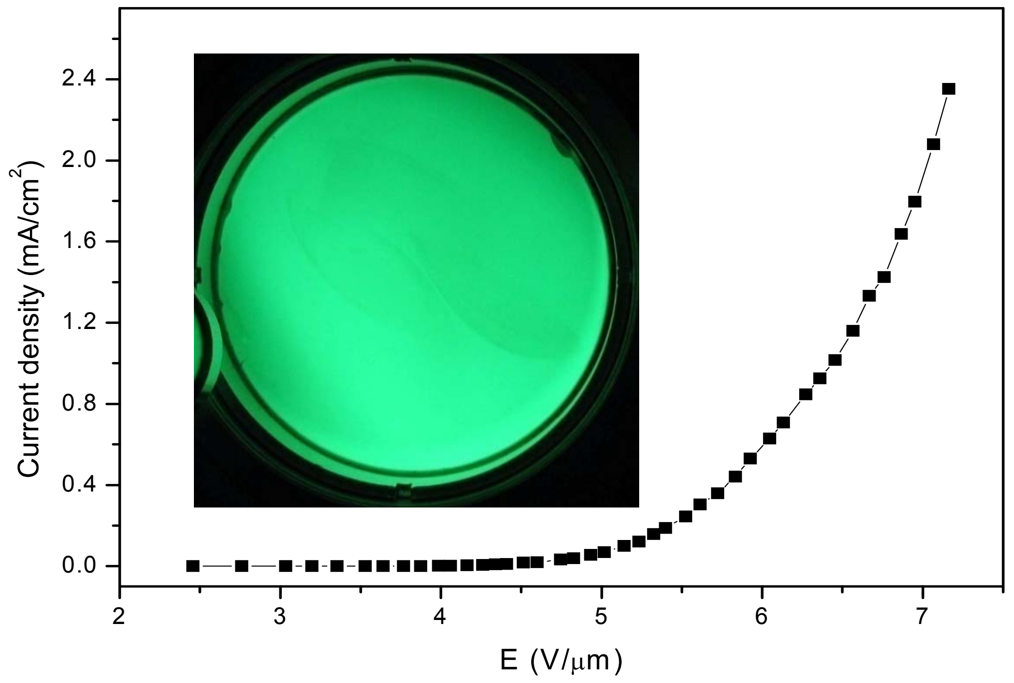
Hong Li[a], Xuejie Huang[a], Liquan Chen[a,*], Guangwen Zhou[b], Ze Zhang[b], Dapeng Yu[c], Yu Jun Mo[d], Ning Pei[d]

[a]*Lab. for Solid State Ionics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China*
[b]*Beijing Laboratory of Electron Microscopy, Center for Condensed Matter Physics, Chinese Academy of Sciences, Beijing 100080, China*
[c]*Department of Physics, National Key Laboratory of Mesoscopic Physics, Peking University, Beijing 100871, China*
[d]*Department of Physics, Henan University, Kaifeng 475001, China*

Field Emission Property of the Nanowires

Efficient field emission from ZnO nanoneedle arrays

Field emission from well-aligned zinc oxide nanowires grown at low temperature , Lee, CJ; Lee, **Applied Physics Letters** 81: 3648, 2002



开启场强：2.4 V/ μm
7 V/μm下的发射电流密度：2.4mA/cm^2

中国专利： **ZL 03 1 49784.5**

49 papers contributed to this field

Appl. Phys. Letters 83,144,2003; 引用 **359**次

Field Emission Property of the Nanowires

APPLIED PHYSICS LETTERS **86**, 203115 (2005)

Morphological effects on the field emission of ZnO nanorod arrays

Q. Zhao, H. Z. Zhang, Y. W. Zhu, S. Q. Feng, X. C. Sun, J. Xu, and D. P. Yu[a)]
Electron Microscopy Laboratory and State Key Laboratory for Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, China

(Received 4 February 2005; accepted 6 April 2005; published online 12 May 2005)

APPLIED PHYSICS LETTERS **88**, 033102 (2006)

Enhanced field emission from ZnO nanorods via thermal annealing in oxygen

Q. Zhao, X. Y. Xu, X. F. Song, X. Z. Zhang, and D. P. Yu[a)]
Electron Microscopy Laboratory, and State Key Laboratory for Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, China

C. P. Li and L. Guo
School of Material Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100083, China

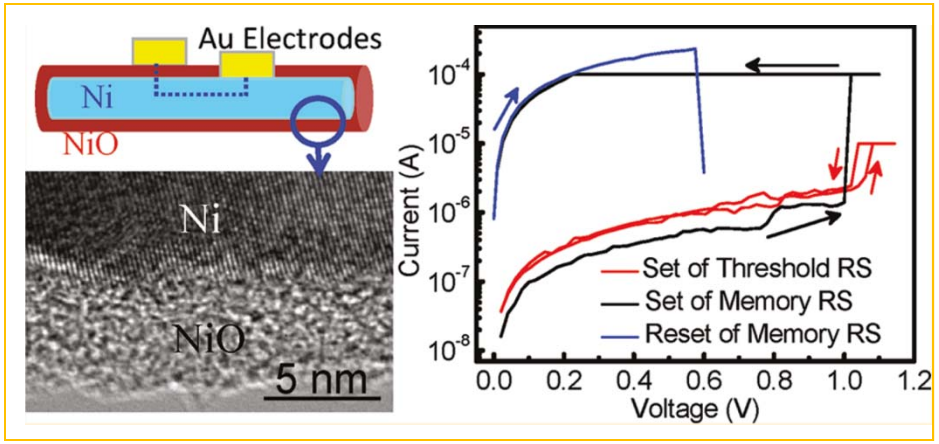
(Received 18 July 2005; accepted 22 November 2005; published online 18 January 2006)

To optimize the field emission behavior of the ZnO nanorods, postthermal annealing in different ambience was conducted. The field emission properties of the ZnO nanorods are considerably improved after annealing in oxygen and getting worse when annealing in air or ammonia. Photoluminescence and Raman spectroscopy were employed to elucidate the reason for such a significant improvement of the field emission when annealing in oxygen. Those detailed analyses suggested that oxygen annealing can reduce the oxygen vacancy concentration, improve the crystal quality, lower the work function, and increase the conductivity of the ZnO nanorods. Our work is important for applications of ZnO nanorods as a promising candidate in flat panel displays and high brightness electron sources. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2166483]

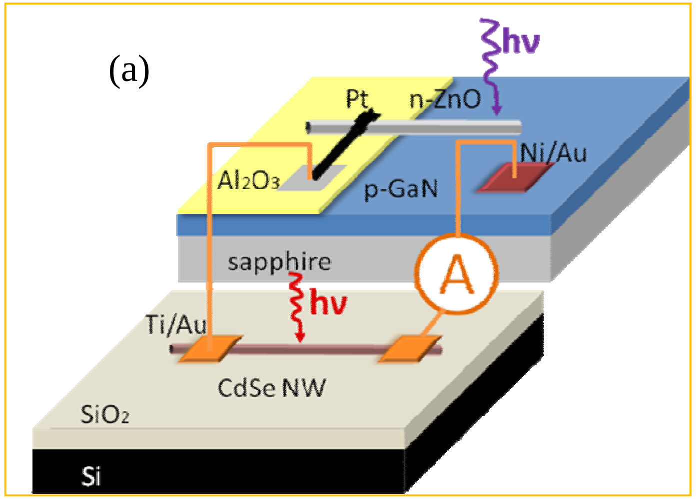
Featured Articles

- **Applied Physics Letters** 83,144, 2003
- **Applied Physics Letters** 72,1835，1998
- **Applied Physics Letters** 83，1689，2003
- **Applied Physics Letters** 85，636， 2004
- **Applied Physics Letters** 82，4146，2003
- **Applied Physics Letters** 85，636，2004
- **Applied Physics Letters** 85，5331， 2004
- **Applied Physics Letters** 85，5682，2004
- **Applied Physics Letters** 86，193101 ，2005；
- **Applied Physics Letters** 86，243103 ，2005；
- **Applied Physics Letters** 86，203115，2005；
- **Applied Physics Letters** 88，033102 ，2006；
- **Journal of Applied Physics** 93，5602，2003；
- **J. Amer. Chemical Society** 127，12452，2005
- **J. Amer. Chemical Society** 127，1120，2005

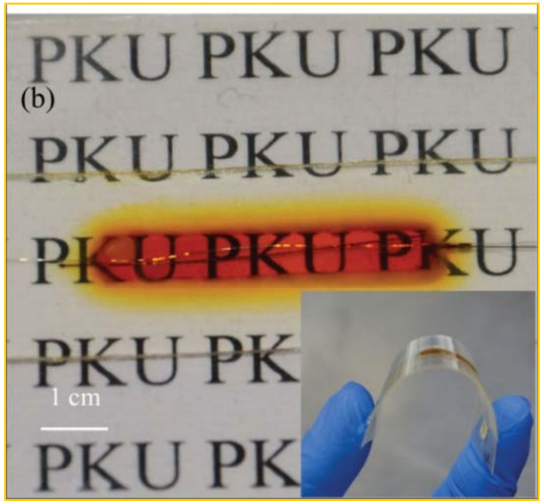
Nanowire Devices



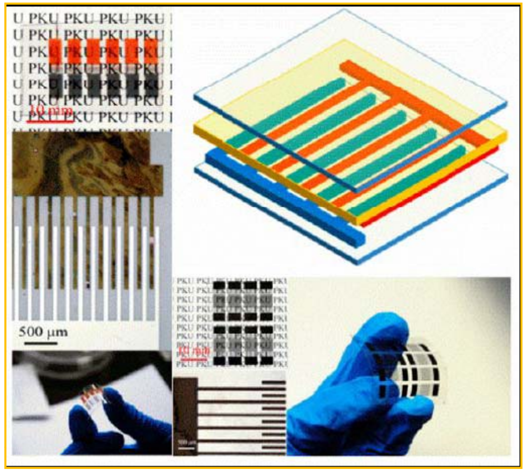
Resistance Switching based on Ni/NiO Core-shell Nanowire
Nano Letters 11, 4601 (2011)



Self-powered Nanodetector based on Nanowire
Advanced Materials 23, 3938 (2011)

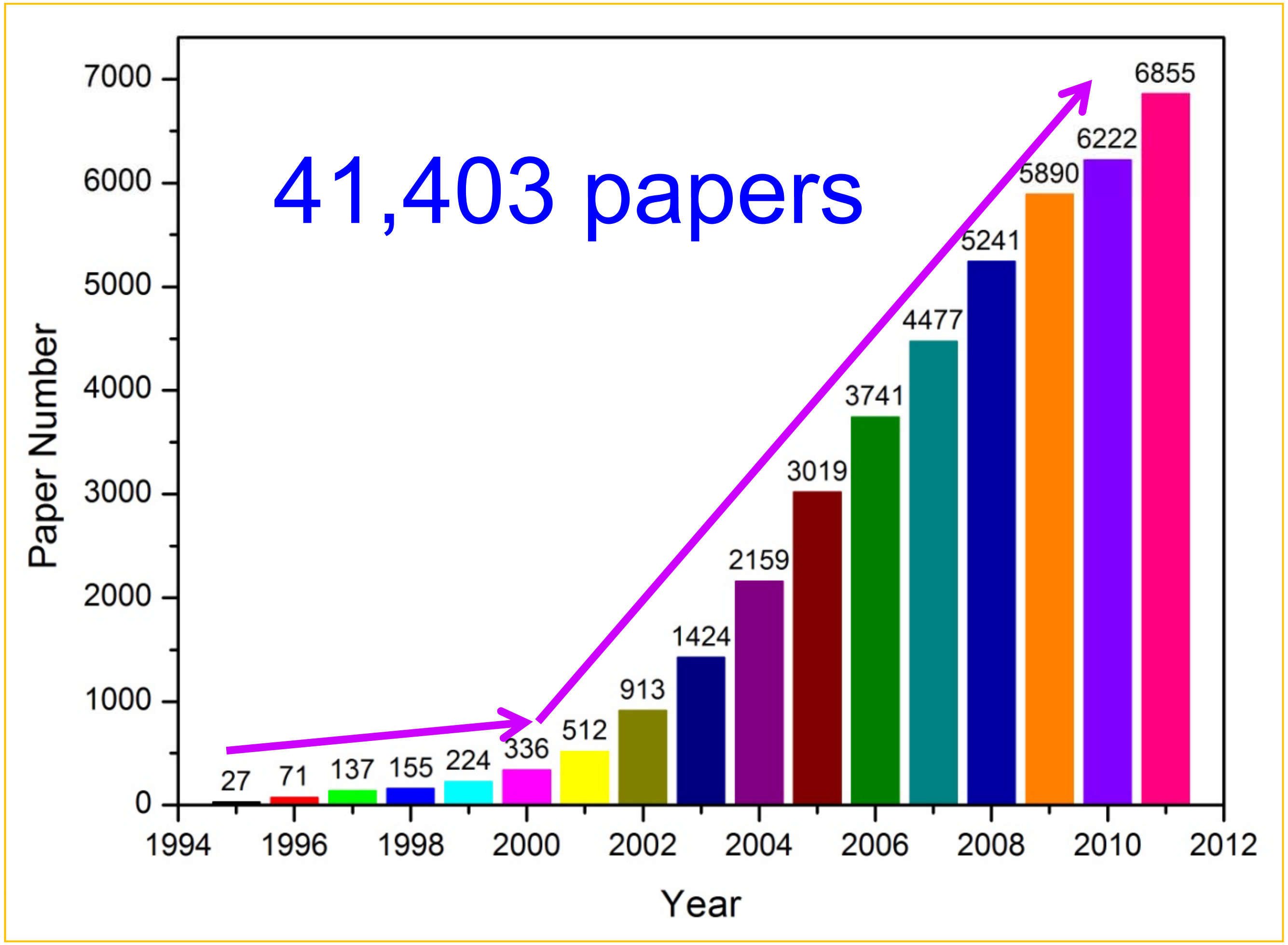


Flexible Nanowire Solar Cells
Advanced Functional Materials 22, 4284 (2012)



Flexible Power Generation/Storage Sources
Nano Letters 13, in press (2013)

Trend of Nanowire Publications



Our Contribution to Nanowire Research

- **Leading contribution in developing method to synthesize 1-dimensional semiconductor nanowires, and to characterize/explore their novelty in properties and potential applications.**
- **365 peer-reviewed papers, including Applied Physics Letters(75), Physical Review B/Letters(16), Advanced Materials(11), Nano Letters(7), and JACS(8).**
- **More than 10000 citations by colleagues worldwide, with a H index = 55.**
- **More than 60 graduates and postdoctoral associates were systematically trained here；培养 青年“千人计划”人才多人.**

Top 10 most cited work in PKU

1. Kong, YC; Yu, DP; Zhang, B; et al.: Ultraviolet-emitting ZnO nanowires synthesized by a physical vapor deposition approach, Applied Physics Letters 78: 407, 2001; 被引频次: 799
2. Wang, JX; Li, MX; Shi, ZJ; et al.: Direct electrochemistry of cytochrome c at a glassy carbon electrode modified with single-wall carbon nanotubes, Analytical Chemistry 74: 1993, 2002;被引频次: 579 .
3. Chen, Q; Zhou, WZ; Du, GH; et al.: Trititanate nanotubes made via a single alkali treatment, ADVANCED MATERIALS 14: 1208, 2002; 被引频次: 490 .
4. Zhang, J; Zou, HL; Qing, Q; et al.:Effect of chemical oxidation on the structure of single-walled carbon nanotubes, Journal of Physical Chemistry B 107: 3712, 2003; 被引频次: 418.
5. Mai, HX; Zhang, YW; Si, R; et al.: High-quality sodium rare-earth fluoride nanocrystals: Controlled synthesis and optical properties, J. American Chemical Society 128: 6426, 2006; 被引频次: 385.
6. Yu, DP; Hang, QL; Ding, Y; Yu, DP;et al.: Amorphous silica nanowires: Intensive blue light emitters, Applied Physics Letters 73: 3076, 1998; 被引频次: 390.
7. Xing, YJ; Xi, ZH; Xue, ZQ; Yu, DP;et al. : Optical properties of the ZnO nanotubes synthesized via vapor phase growth: Applied Physics Letters 83: 1689, 2003; 被引频次: 348.
8. Zhu, YW; Zhang, HZ; Sun, XC; Yu, DP;et al.: Efficient field emission from ZnO nanoneedle arrays, Applied Physics Letters 83: 144, 2003;被引频次: 350.
9. Liu, ZF; Shen, ZY; Zhu, T; et al. : Organizing single-walled carbon nanotubes on gold using a wet chemical self-assembling technique: Langmuir 16: 3569, 2000; 被引频次: 302.
10. Sun, Wen-Tao; Yu, Yuan; Pan, Hua-Yong; et al. : CdS quantum dots sensitized TiO2 nanotube-array photoelectrodes, J. American Chemical Society 130: 1124, 2008; 被引频次: 298.

Recent Representative Work

1. Novel Planar-Structure Electrochemical Devices for Highly Flexible Semitransparent **Power Generation Storage Sources** Heng Li, Qing Zhao, Wei Wang, Hui Dong,Dongsheng Xu, Guijin Zou, Huiling Duan,Dapeng Yu, **Nano Letters** 13: in press， 2013
2. **Strain-Gradient Effect** on Energy Bands in Bent ZnO Microwires, Han, Xiaobing; Kou, Liangzhi; Zhang, Zhuhua; 等., **Advanced Materials** 24: 4707-4711，2012
3. Large Magnetoresistance in Few Layer **Graphene** Stacks with Current Perpendicular to Plane Geometry, Liao, Zhi-Min; Wu, Han-Chun; Kumar, Shishir; 等., **Advanced Materials** 24: 1862-1866, 2012
4. Tunable Bandgap **in Silicene and Germanene**, Ni, Zeyuan; Liu, Qihang; Tang, Kechao; 等，**Nano Letters** 12: 113-118, 2012
5. **Memory** and Threshold **Resistance Switching** in Ni/NiO Core-Shell Nanowires, He, Li; Liao, Zhi-Min; Wu, Han-Chun; 等., **Nano Letters** 11: 4601-4606, 2011
6. **Site-Specific Transfer-Printing** of Individual Graphene Microscale Patterns to Arbitrary Surfaces, Bie, Ya-Qing; Zhou, Yang-Bo; Liao, Zhi-Min; 等., **Advanced Materials** 23: 3938, 2011
7. Vertical Plasmonic Resonant **Nanocavities**, Zhu, Xinli; Zhang, Jiasen; Xu, Jun; 等., **Nano Letters** 11: 1117-1121, 2011.
8. **Self-Powered**, Ultrafast, Visible-Blind UV Detection and Optical Logical Operation based on ZnO/GaN Nanoscale p-n Junctions, Bie, Ya-Qing; Liao, Zhi-Min; Zhang, Hong-Zhou; 等., **Advanced Materials** 23: 649， 2011.
9. Ultrafine and Smooth Full Metal Nanostructures for **Plasmonics**, Zhu, Xinli; Zhang, Yang; Zhang, Jiasen; 等**Advanced Materials** 22: 4345, 2010
10. Single ZnO Nanowire/p-type GaN Heterojunctions for **Photovoltaic Devices** and UV Light-Emitting Diodes, Bie, Ya-Qing; Liao, Zhi-Min; Wang, Peng-Wei; 等，**Advanced Materials** 22 : 4284, 2010
11. Confined Three-Dimensional **Plasmon Modes** inside a Ring-Shaped Nanocavity on a Silver Film Imaged by Cathodoluminescence Microscopy, Zhu, X. L.; Ma, Y.; Zhang, J. S.; 等., **Physical Review Letters** 105: 127402,2010
12. Evidence for Thermal Spin-Transfer Torque, Yu, Haiming; Granville, S.; Yu, D. P.; 等., **Physical Review Letters** 104: 146601, 2010
13. **Electronic and Mechanical Coupling** in Bent ZnO Nanowires, Han, Xiaobing; Kou, Liangzhi; Lang, Xiaoli; 等., **Advanced Materials** 21: 4937, 2009
14. Electrical and Photoresponse Properties of an Intramolecular **p-n Homojunction** in Single Phosphorus-Doped ZnO Nanowires, Li, Ping-Jian; Liao, Zhi-Min; Zhang, Xin-Zheng; 等., **Nano Letters** 9: 2513-2518, 2009
15. **MgB2 Superconducting Whiskers** Synthesized by Using the Hybrid Physical-Chemical Vapor Deposition,Wang, Yazhou; Zhuang, Chenggang; Gao, Jingyun; 等., **Journal of The American Chemical Society** 131: 2436,2009

Outline

- Why Nanowires?
- Our contribution to world research;
- Recent Progress in fine nanostructure study via high spatial/energy Cathodoluminescence;
- Summary

Recent Progress

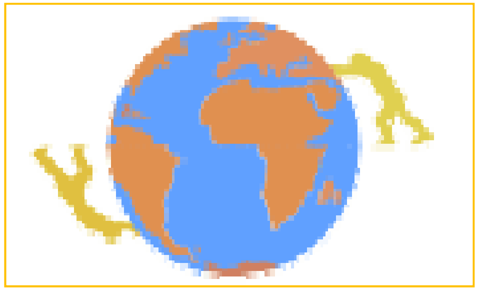
1. **Strain modification on the emission energy in ZnO Nano/microwires**

2. **Directly "see" the resonant SPP modes confined in metal nanocavities**

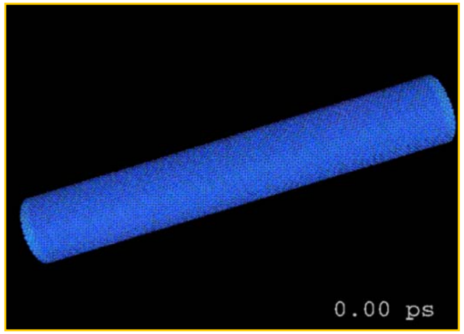
Strain Effect in Materials

应变存在的普遍性

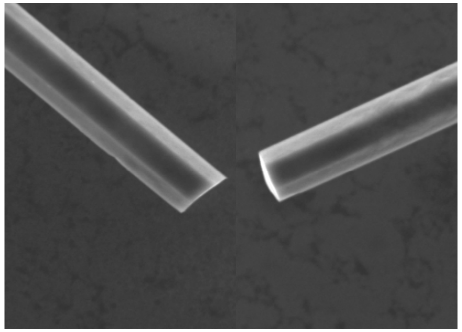
应变作用的两面性



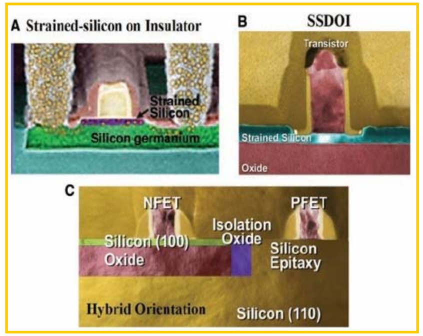
地壳运动



分子的受力变形

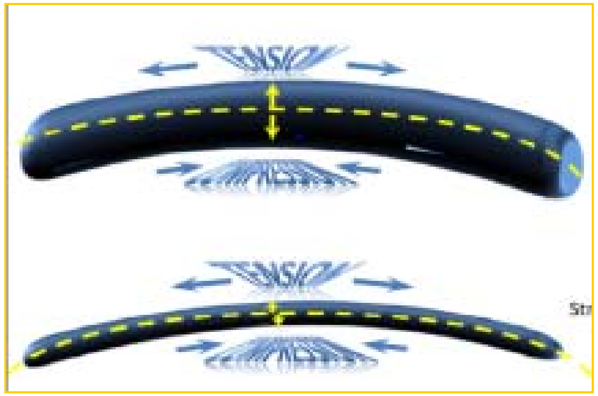


应变导致材料器件失效



应变工程-奔腾“4”处理器

Science 2004, 306, 20570



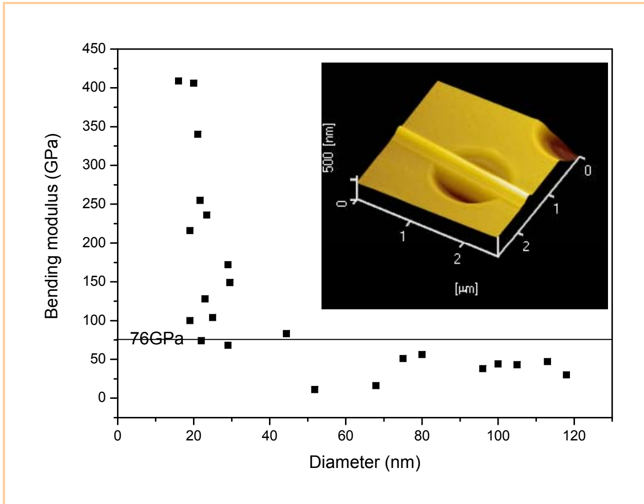
Young's Modulus

Distance to neutral axis

$$\sigma = E\, y / R$$

Stress

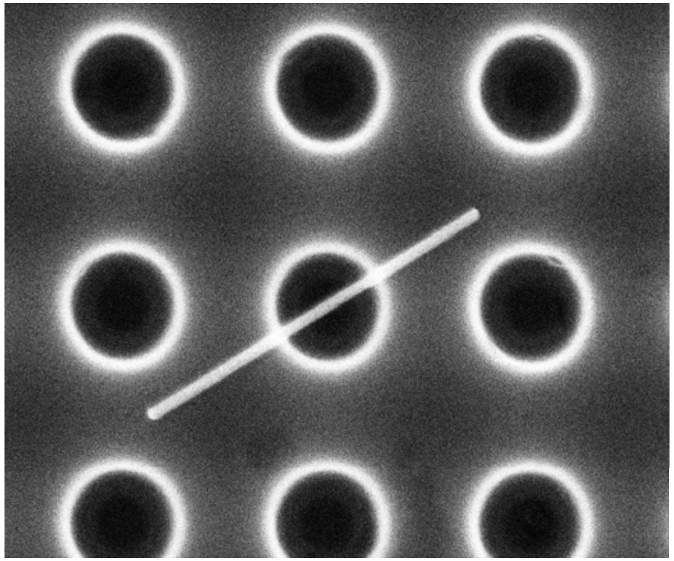
Radius of Curvature

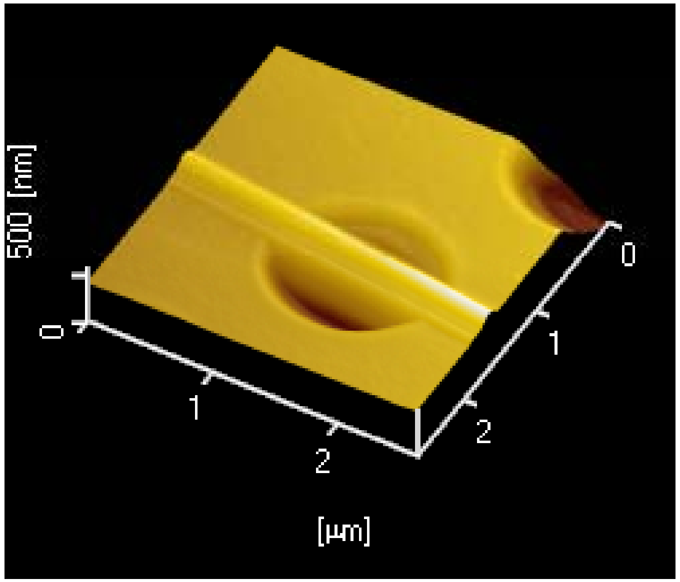


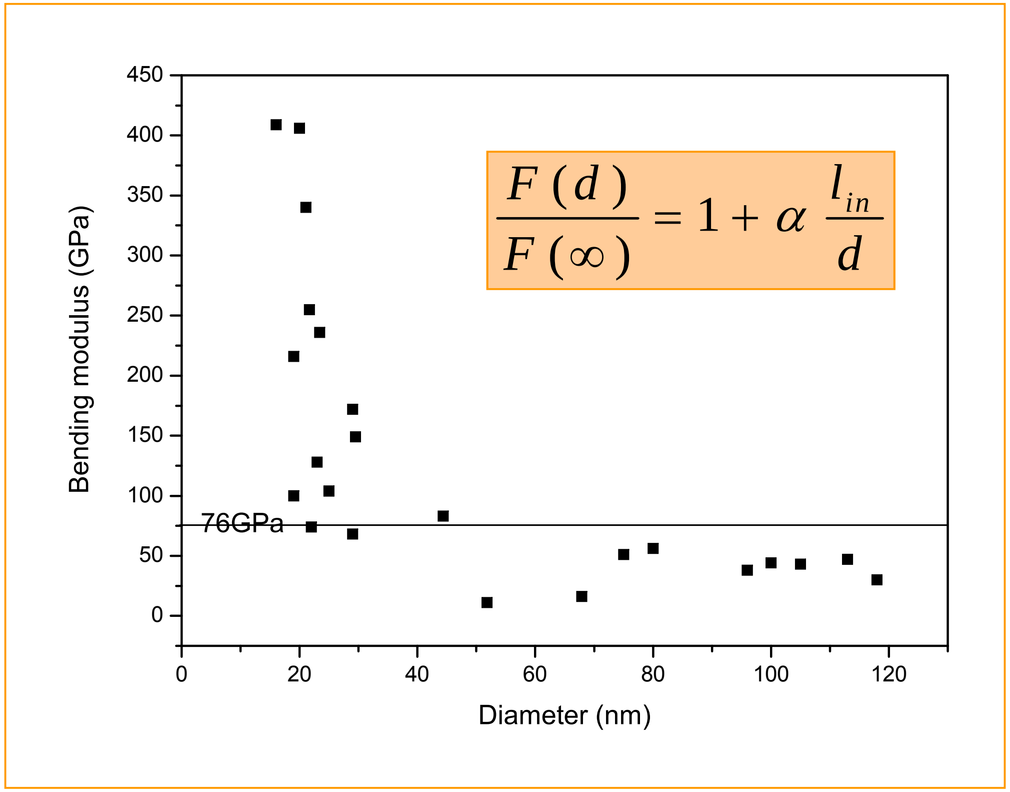
应变的尺寸效应：小尺度，大应变

杨氏弯曲模量的尺寸效应

Size effect in mechanical properties of Ag nanowires

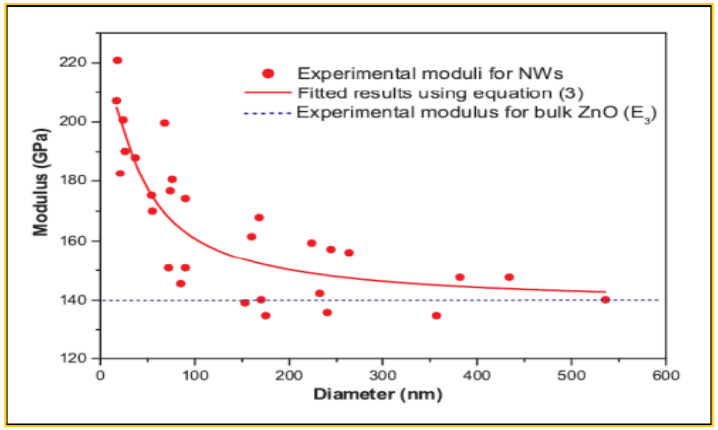


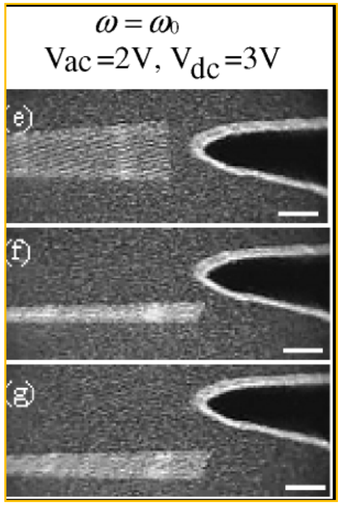


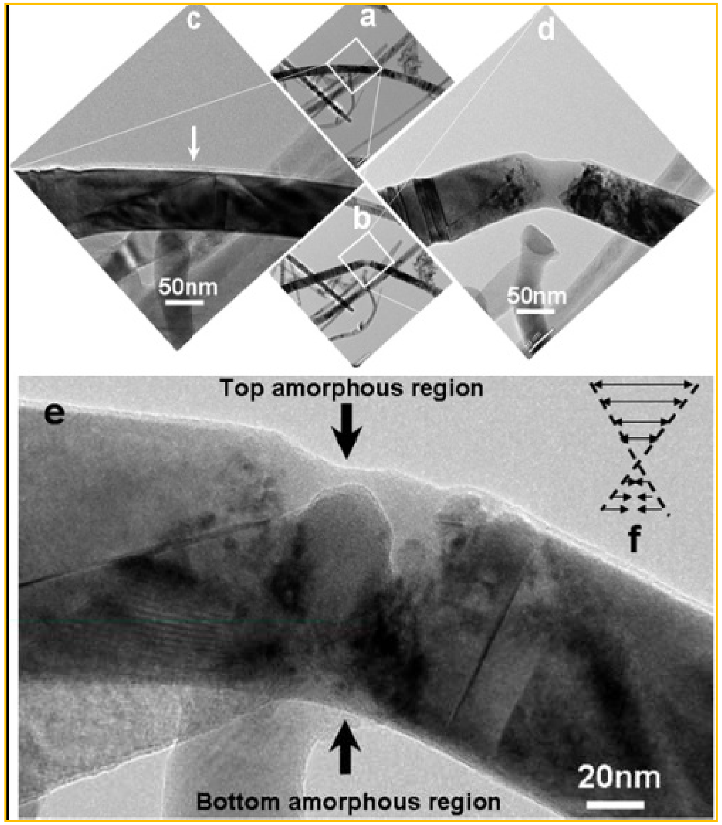


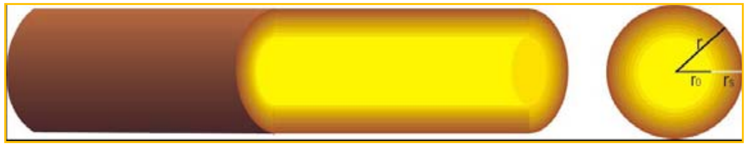
G.Y. Jing et al., Physical Review B 73, 235409(2006)

Size effect in mechanical properties of ZnO and SiC nanowires







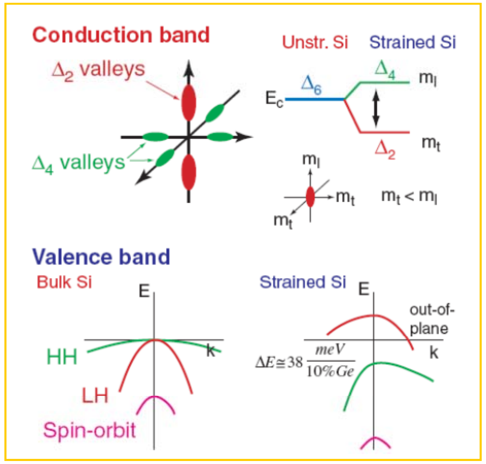


Young's Modulus increases dramatically with the decreasing diameters

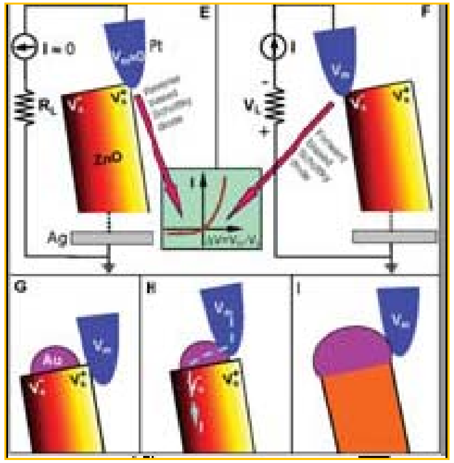
Unusually large strain plasticity of ceramic SiC nanowires

C. Q. Chen et al., PRL 96, 075505 (2006). **X. D. Han et al., Nano Letters 7, 452 (2007).**

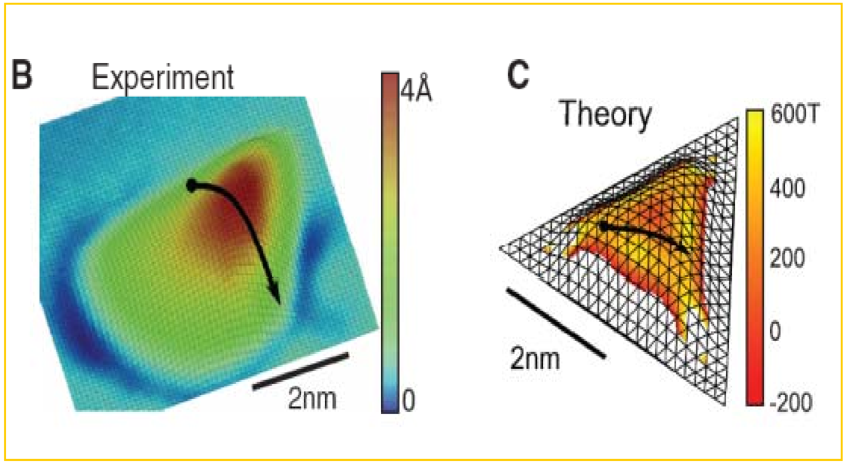
Strain Effect in Nanostructure



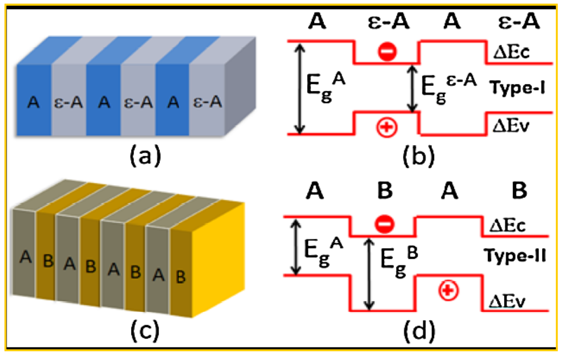
Crystal field symmetry
Science 2004, 306, 2057



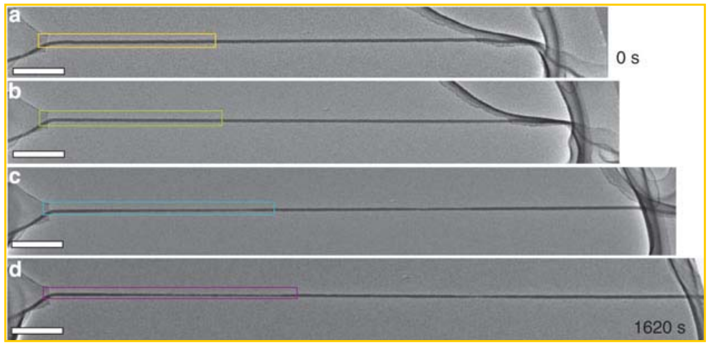
Nanogenerators
Science 2006, 312, 242



Giant Pseudo magnetic field
Science 2010, 329, 544



Strain superlattice
PRL 2010, 105: 0168026

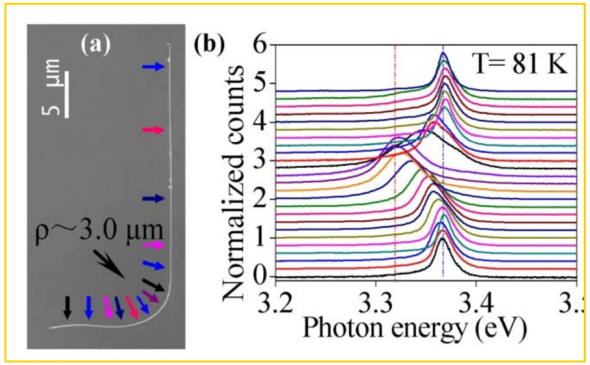


Super plasticity
Nature Comm.2010, 1, 1038

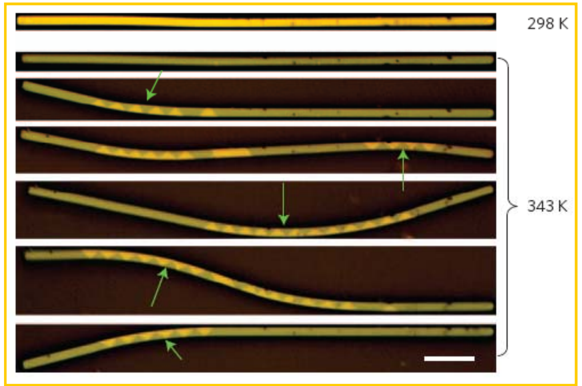
Flexible devices

Why Bending？ —very rich physical Phenomena

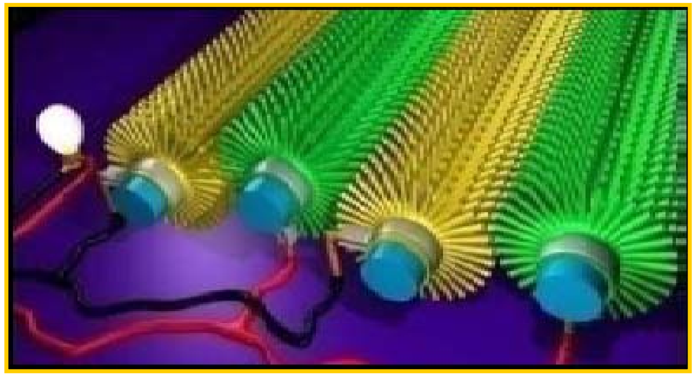
Strain tuned band-gap
Advanced Mater.2009, *4*, 7302

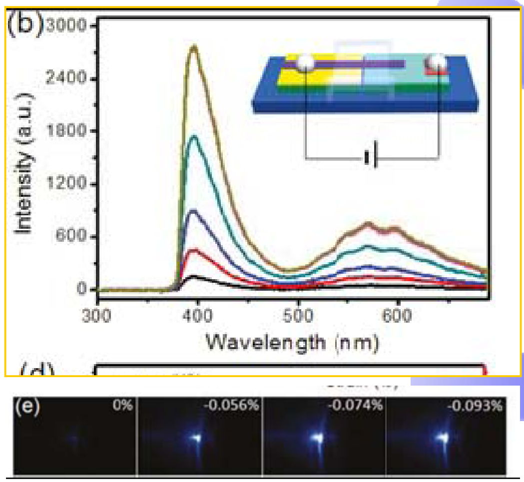


Metal-insulator transition
Nature Nanotec.2009, *4*, 7302



Nanogenerators
Nature 451,809，2008





Strain enhanced LED
Nano Lett. 2011, 11,4012

Men-made mussles

PERGAMON

Early Work

Solid State Communications 124 (2002) 417–421

solid state communications

www.elsevier.com/locate/ssc

Localized cathodoluminescence investigation on single Ga_2O_3 nanoribbon/nanowire

D.P. Yu[a,b,*], J.-L. Bubendorff[c], J.F. Zhou[b], Y. Leprince-Wang[a], M. Troyon[c]

[a]*Laboratoire de Physique des Matériaux Divisés et des Interfaces, Université de Marne-La-Vallée, 5, Bd. Descartes, 77454 Marne-la-Vallee Cedex 2, France*

[b]*School of Physics, State Key Laboratory for Mesoscopic Physics, and Electron Microscopy Laboratory, Peking University, Beijing 100871, People's Republic of China*

[c]*Unité de Thermique et Analyse Physique, EA 2061, Université de Reims, 21 rue Clément Ader, 51685 Reims Cedex 2, France*

Received 20 July 2002; accepted 30 August 2002 by Z. Gan

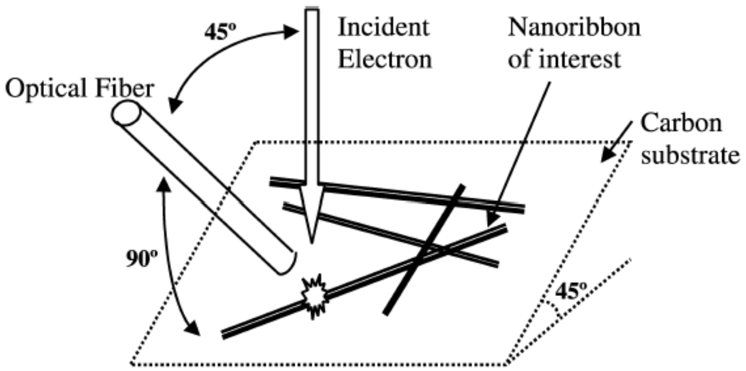
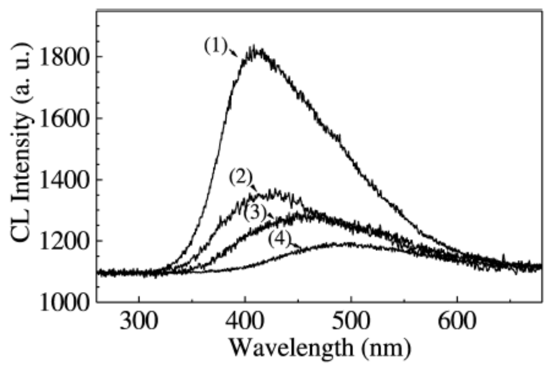
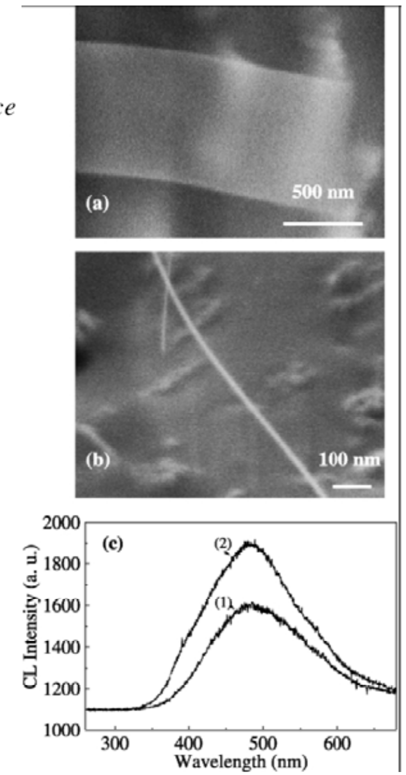
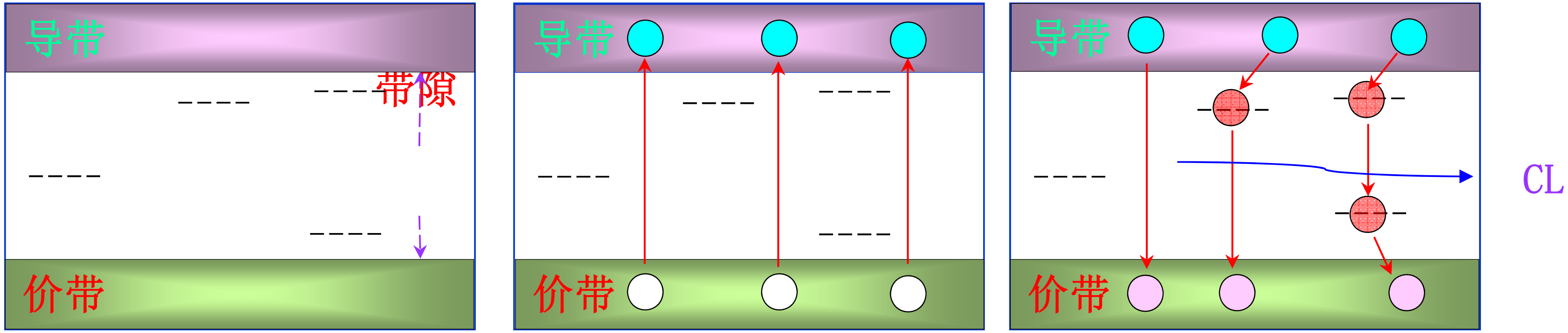


Fig. 1. Schematic presentation of the experimental setting for local collection of the CL on selected Ga_2O_3 nanoribbons/wires.





Principle of the CL in semiconductors



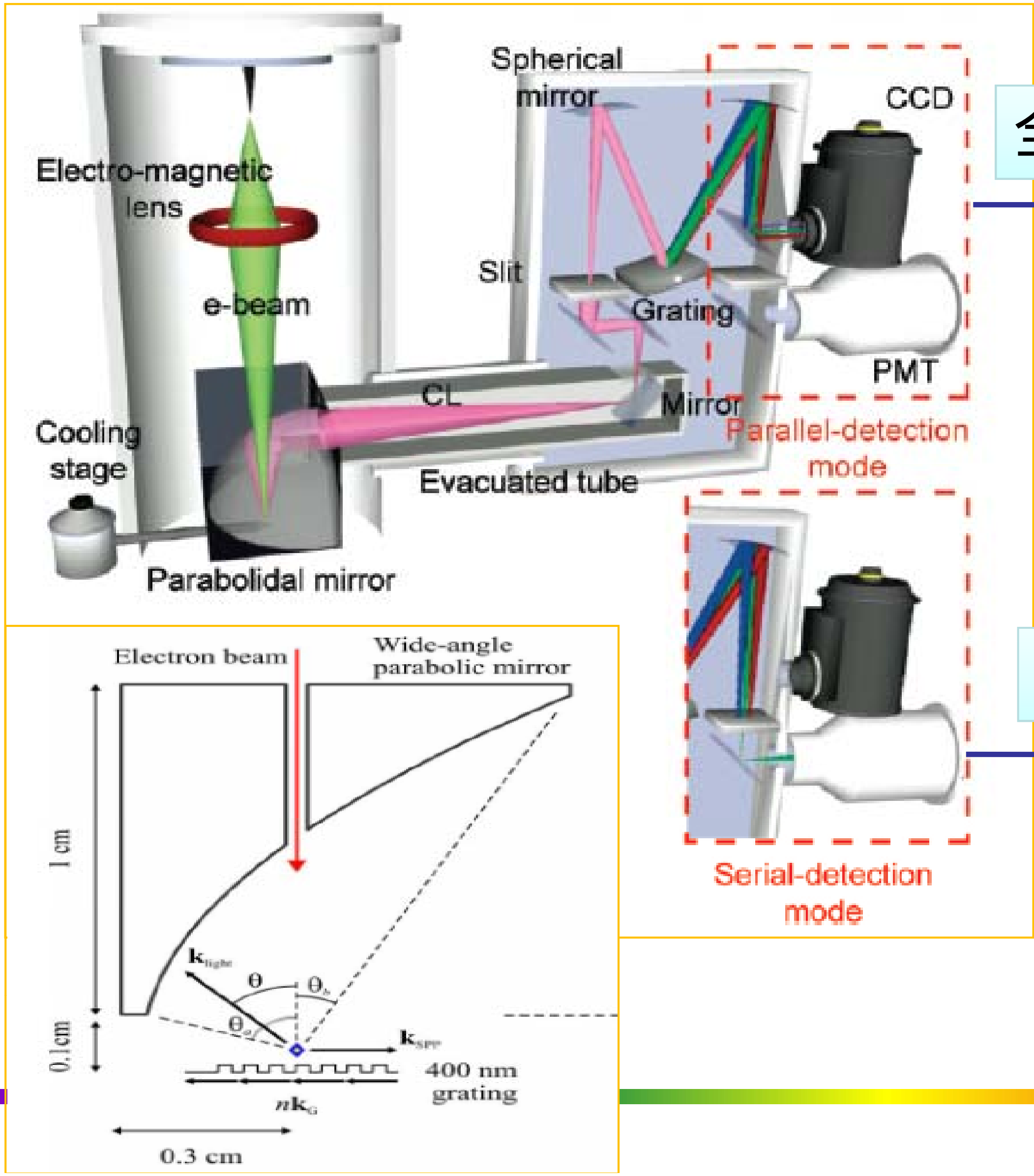
（a）： Band structure with defect levels；

（b）： Excitation；

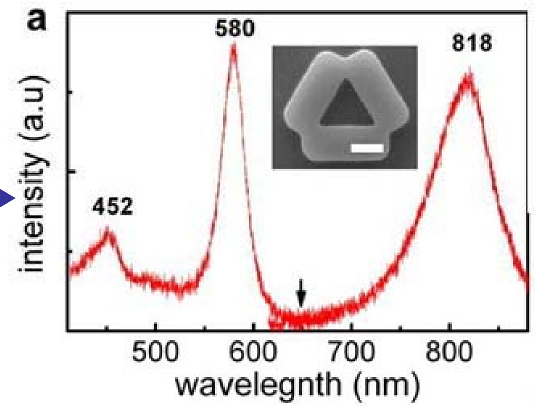
（c）： Recombination

Low temperature CL analysis can reveal the fine electronic structure of the semiconductor materials.

Cathodoluminescence（CL）

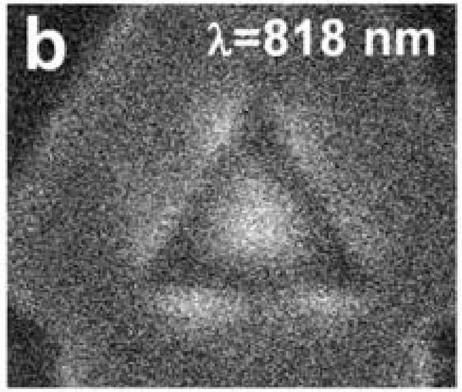


全谱



CL共振全谱

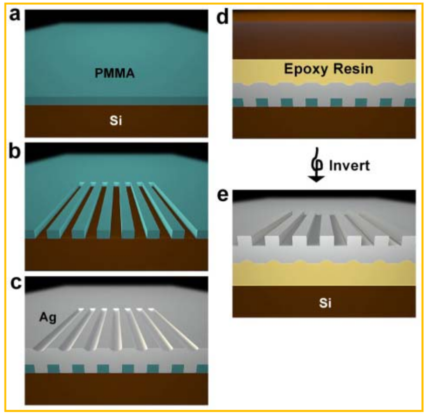
单色

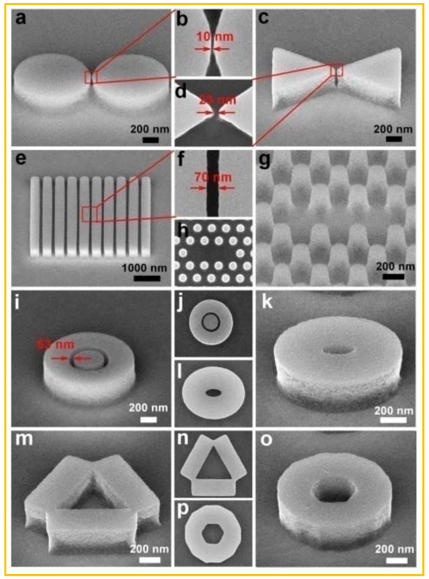


单色共振模式

Nanophotonics

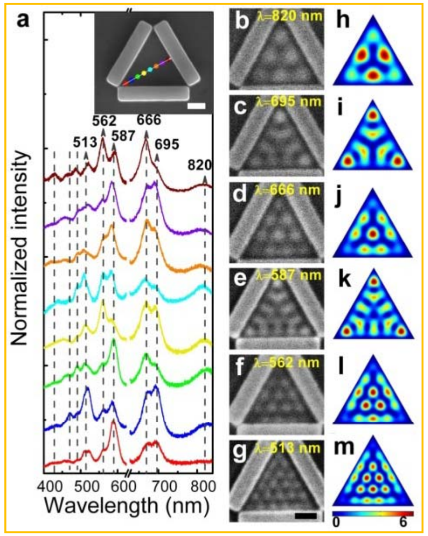
A Template Stripping Method to Fabricate Ultra Smooth Metal Nanocavity

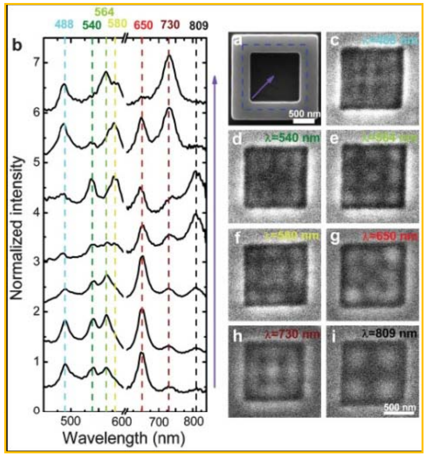




朱新利 等, Advanced Materials 22,4345(2010)

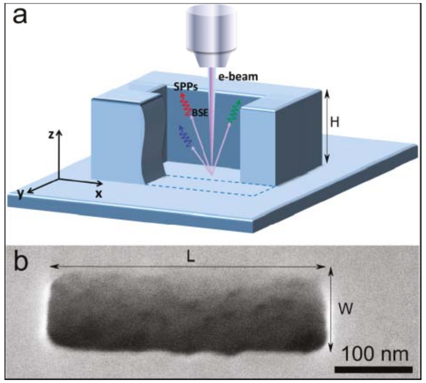
"Seeing" the Plasmon Resonant Modes Confined inside a Ring-Shaped Nanocavity



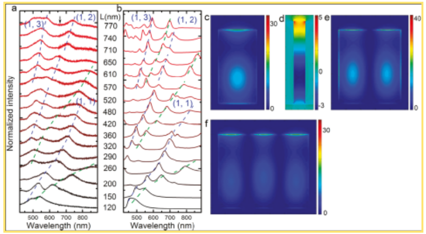


朱新利 等, Physical Review Letters 10, 127402(2010)

Vertical Plasmonic Resonant Modes in Silver Nanocavities



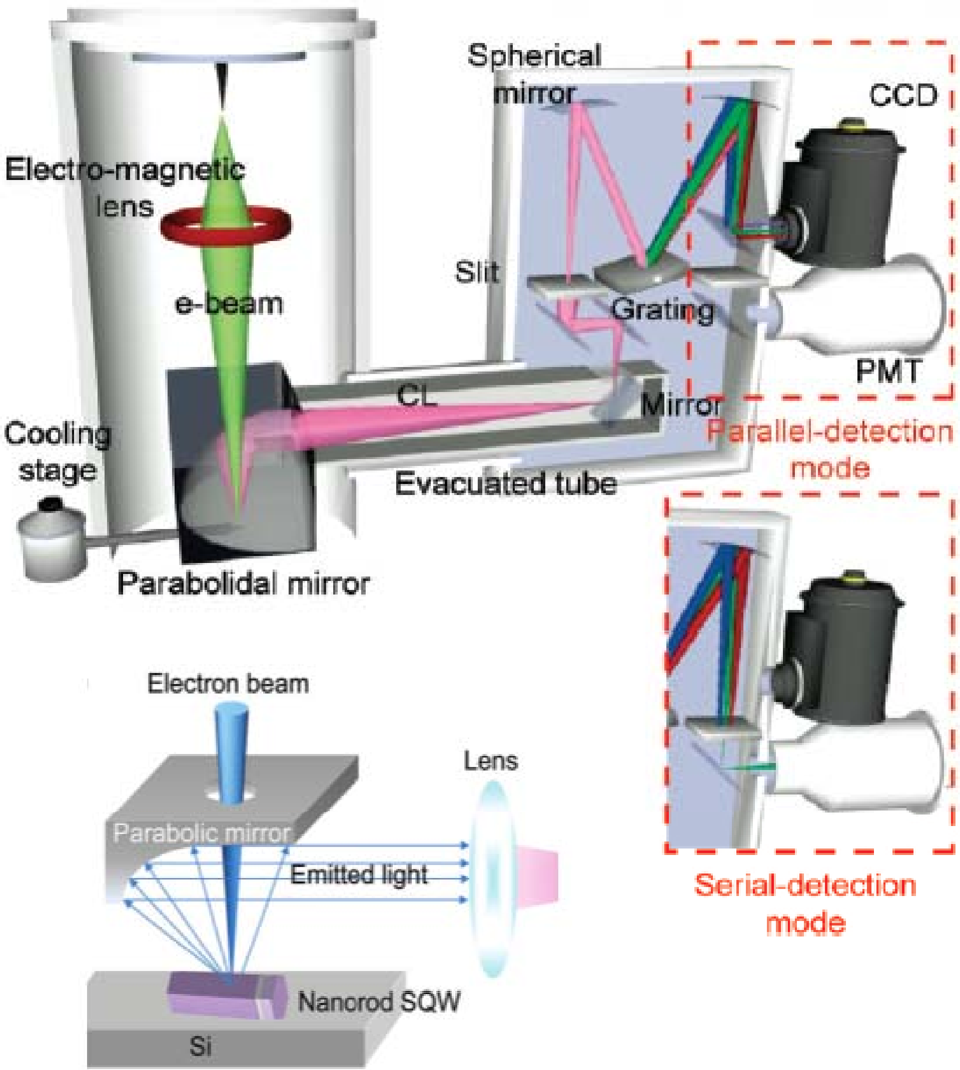
Plasmonic vertical nanocavity. (a) Schematic of a single nanocavity and excitation of SPPs with backscattered electrons.



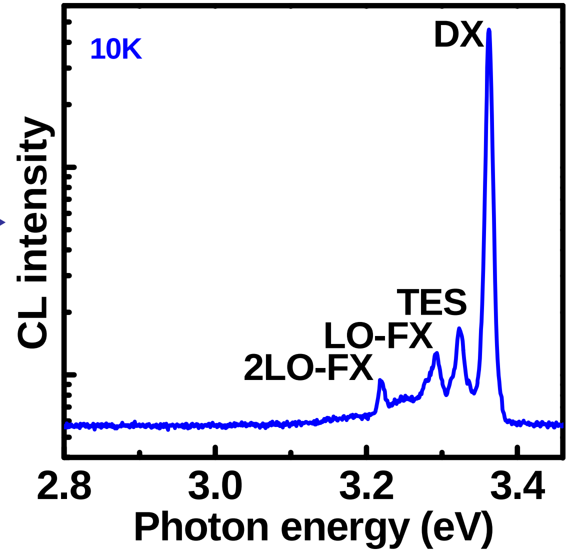
Resonances and mode patterns of plasmonic nanocavities with 70 nm widths, 500 nm heights, and increasing lengths.

朱新利 等, Nano Letters 11, 1117(2011).

Cathodoluminescence Setup

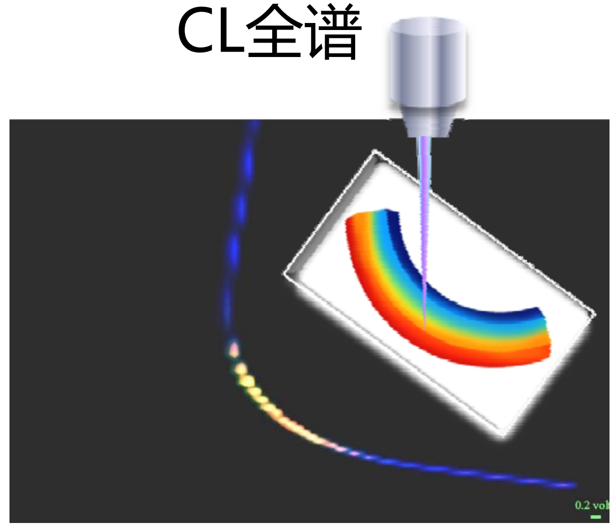


全谱



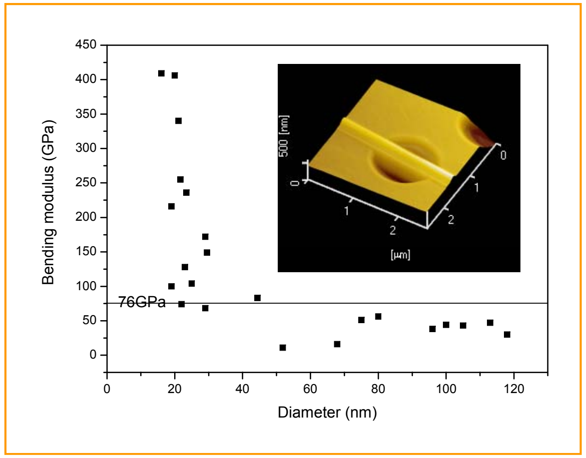
CL全谱

单色

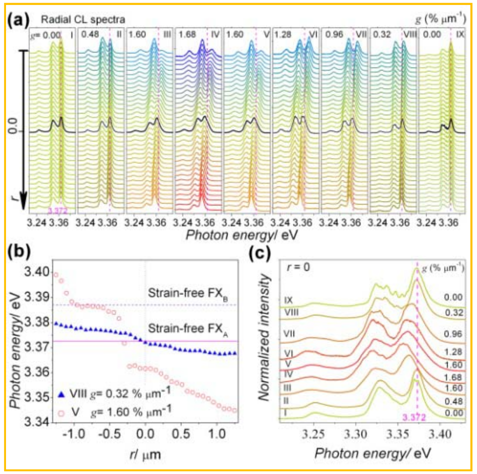


CL mapping

Strain Modification of the Electronic structure of the semiconductor nano/microwires

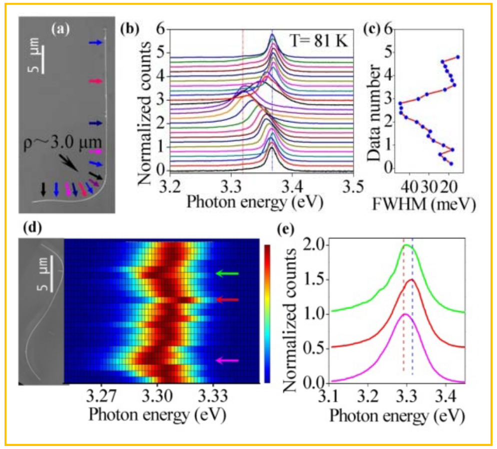


Physical Review B 73, 235409(2006)

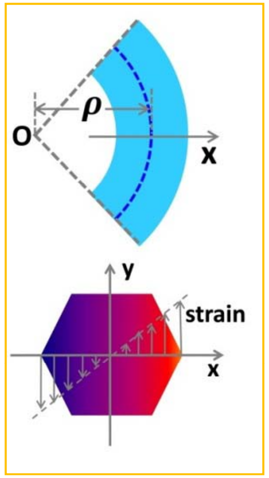


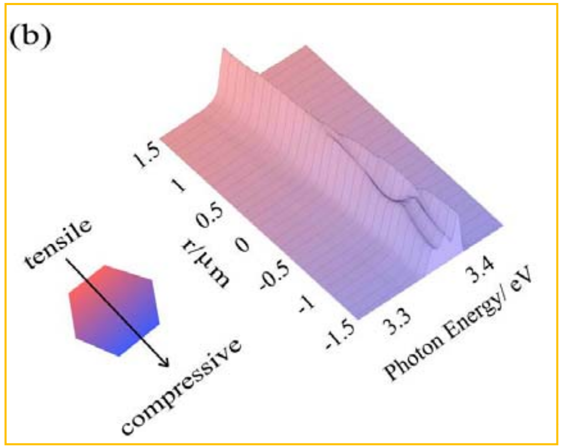
Advanced Materials 24, 4707，2012

Strain Gradient Effects



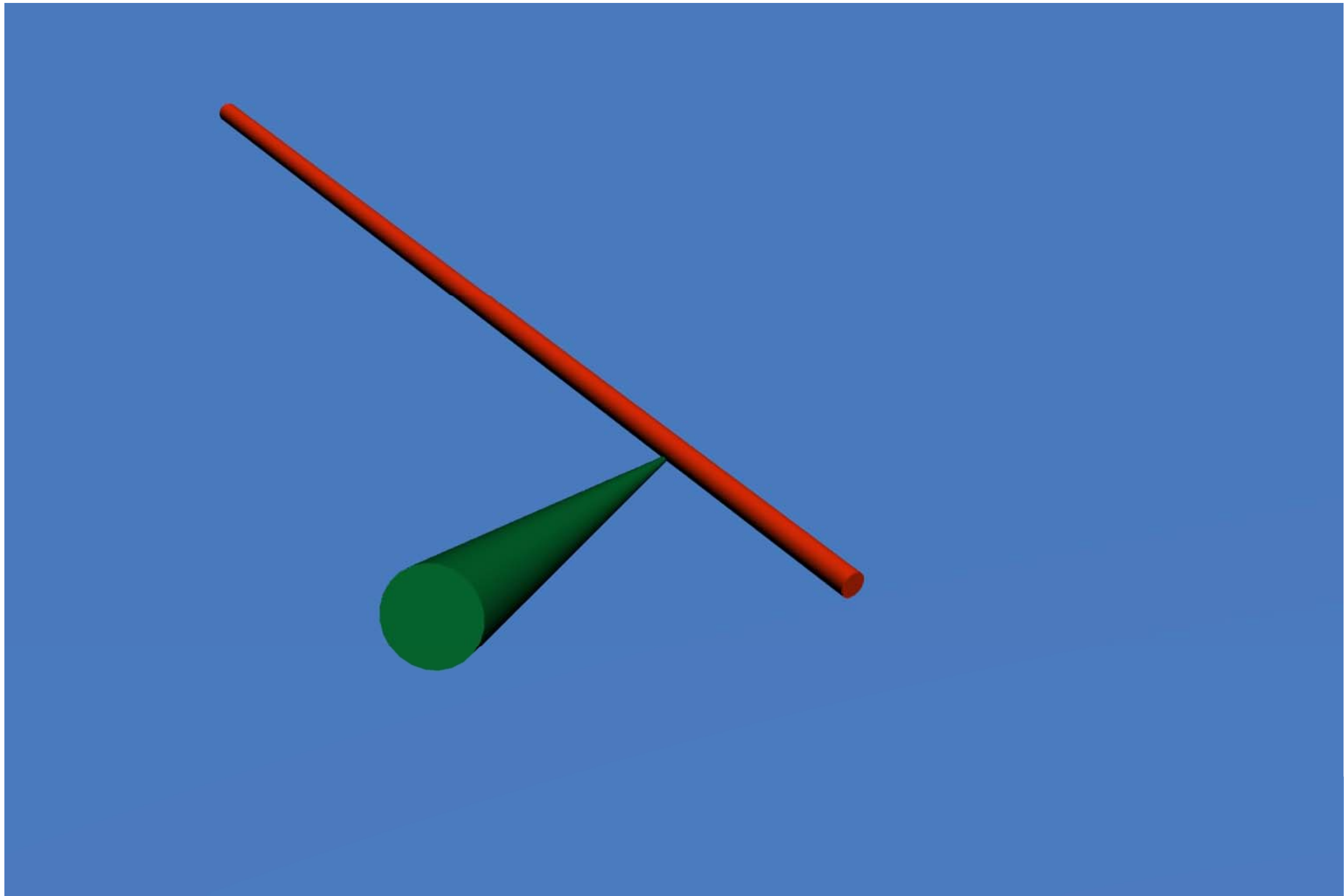
Advanced Materials 21, 4937，2009

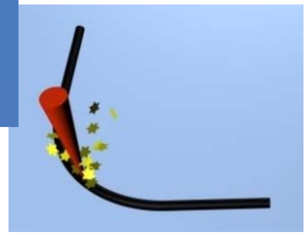




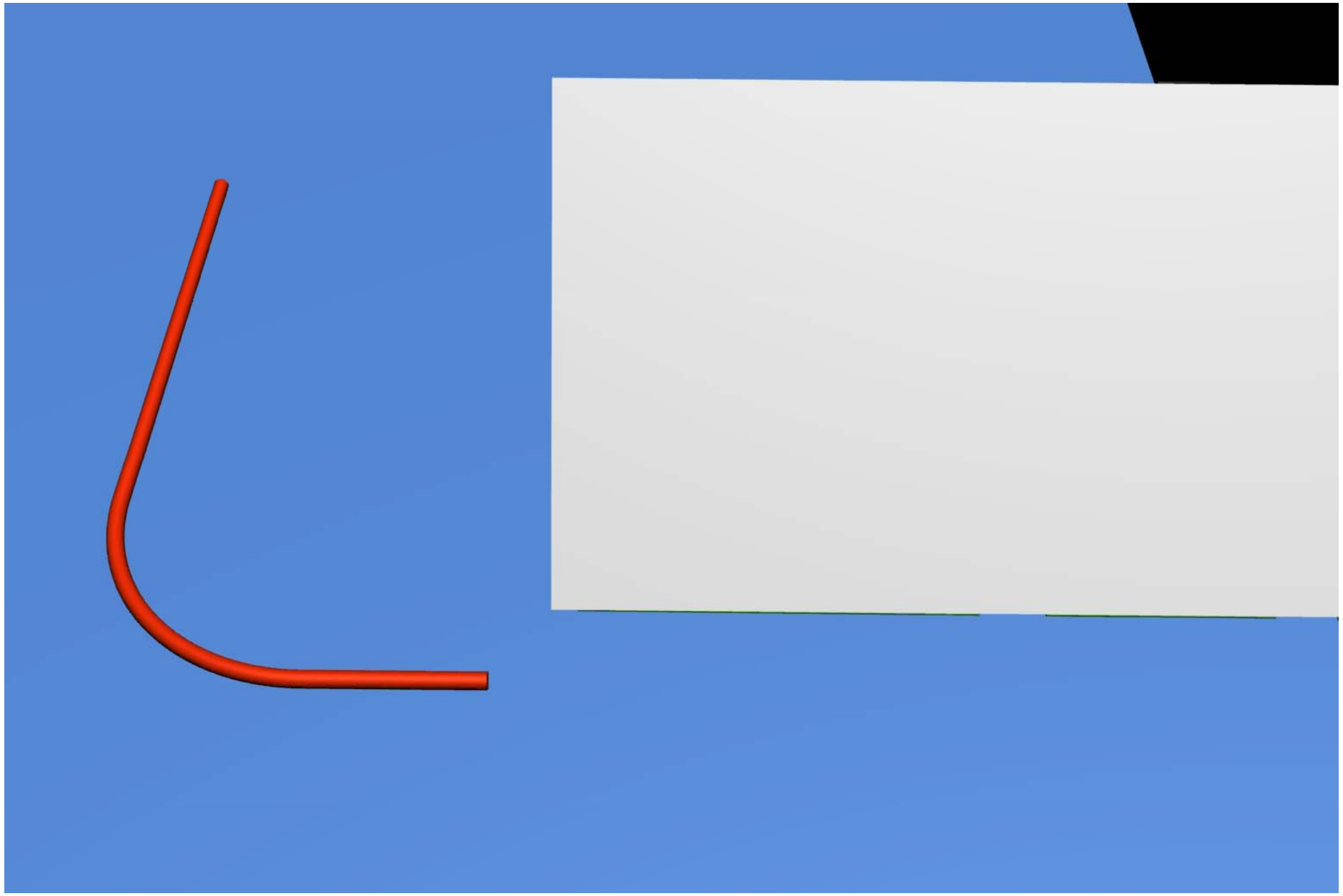
Scientific Reports 2, 452，2012
Nature Publishing Group

Elastic Bending Deformation

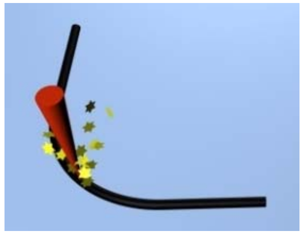




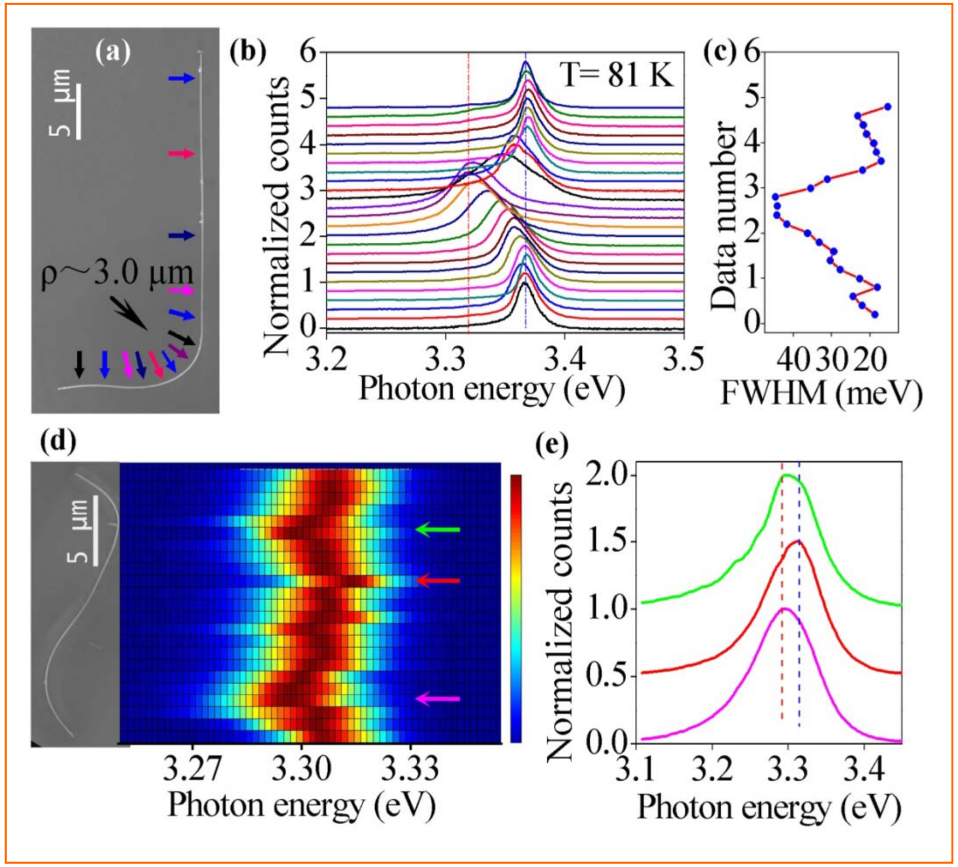
Peak shift and broadening as function of the bending strain

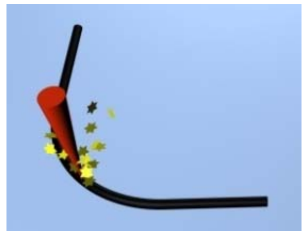


Video



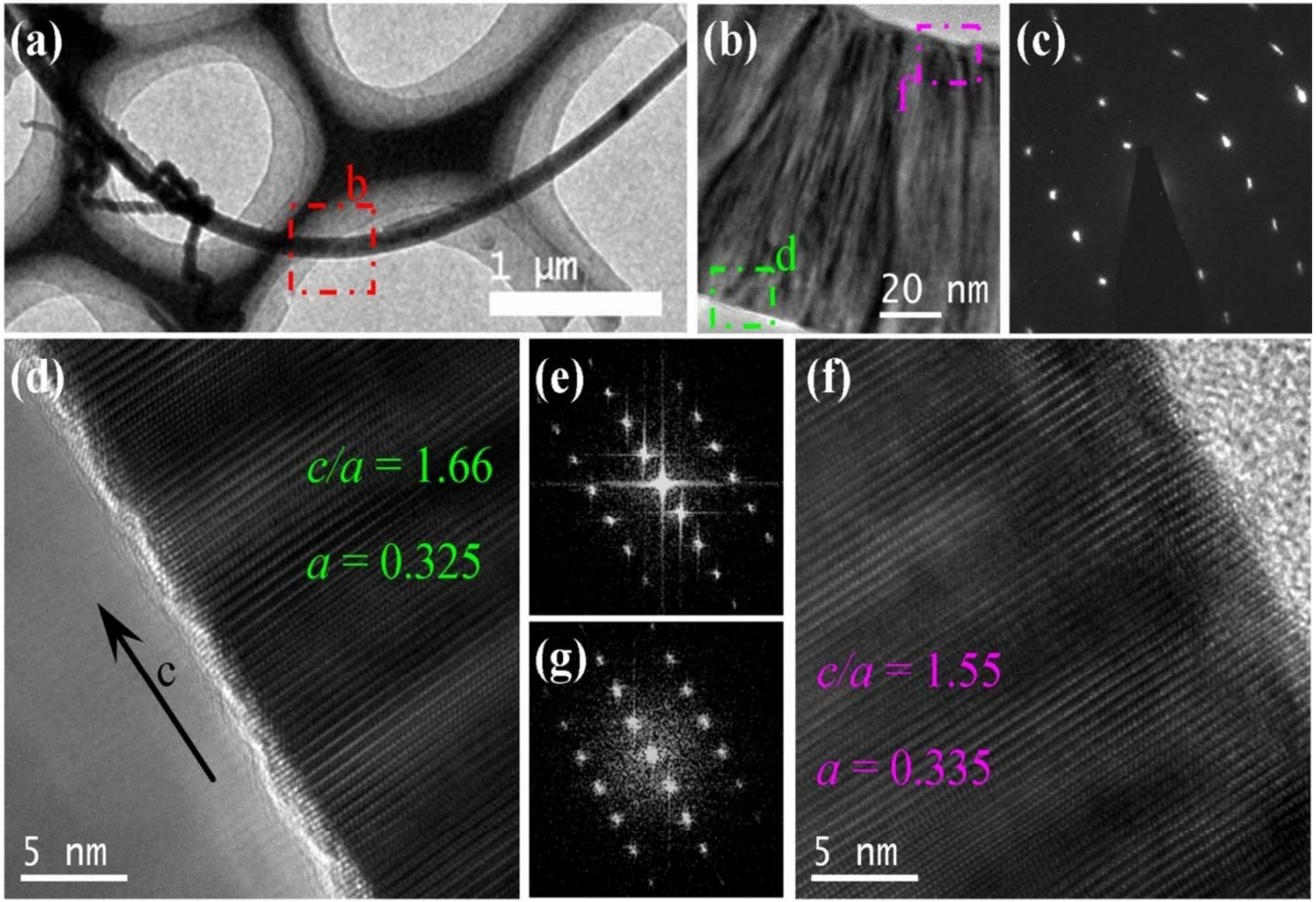
Peak shift and broadening as function of the bending strain



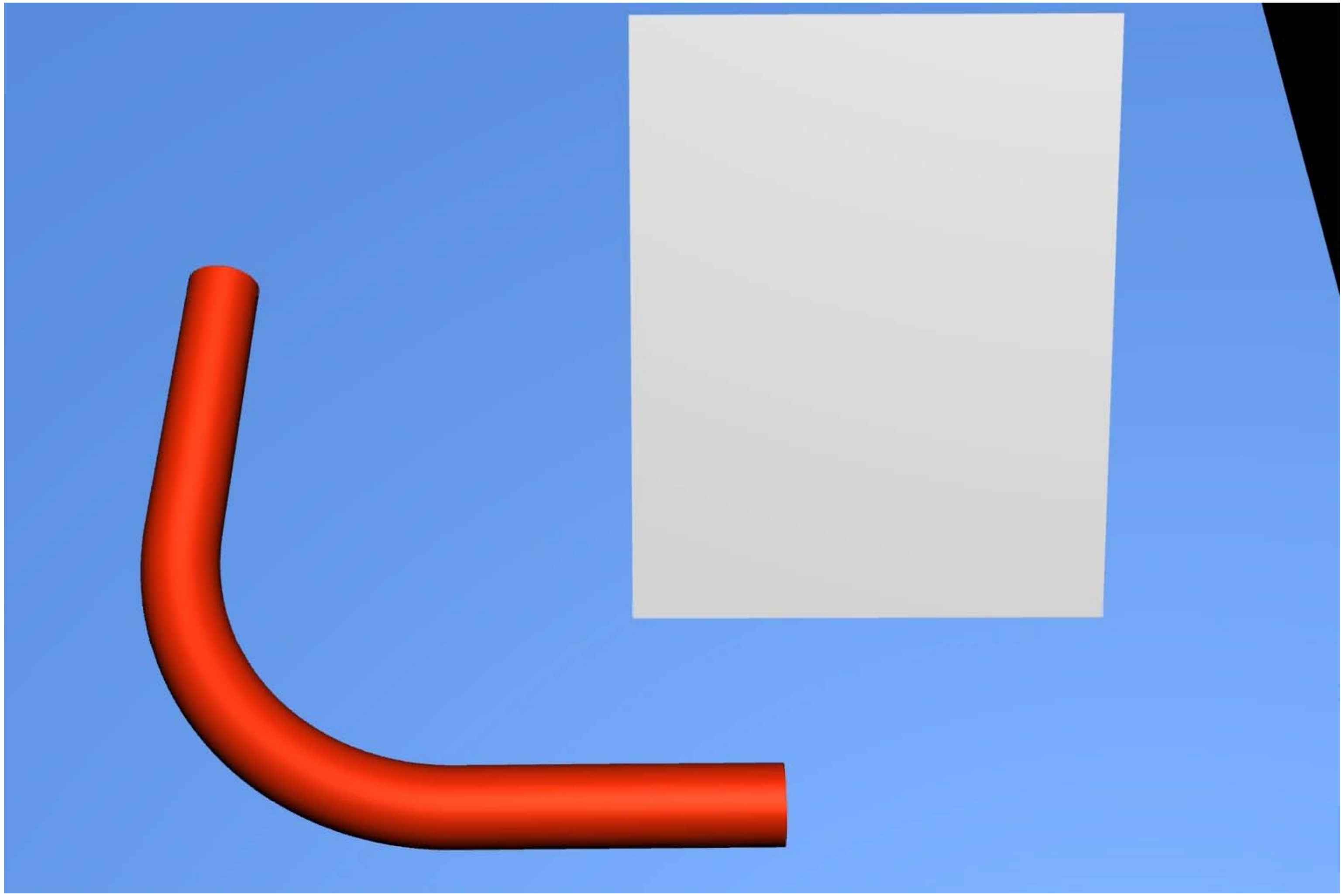


Xiaobing Han et al., Advanced Materials 21, 4937，2009

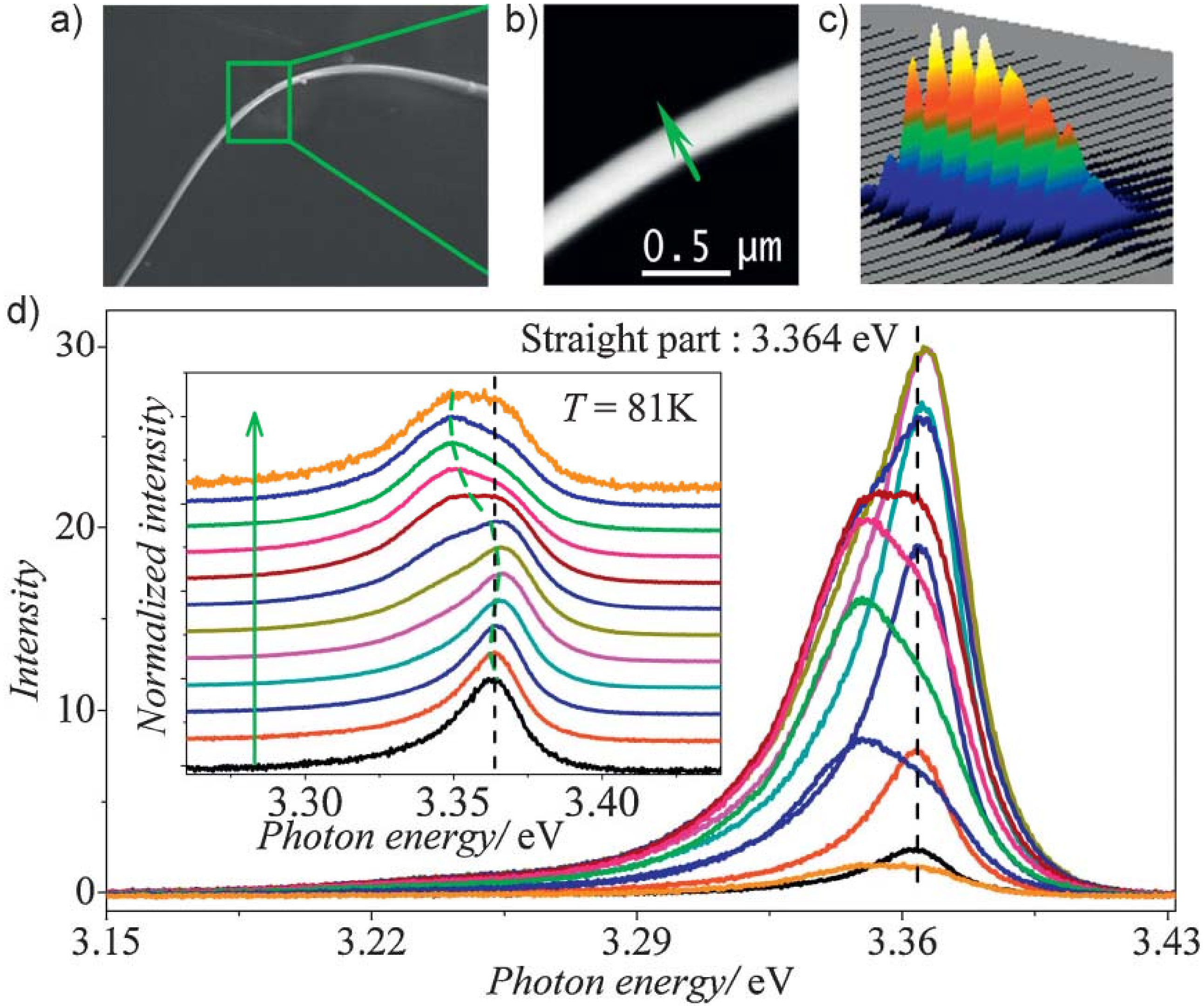
In situ TEM Analysis



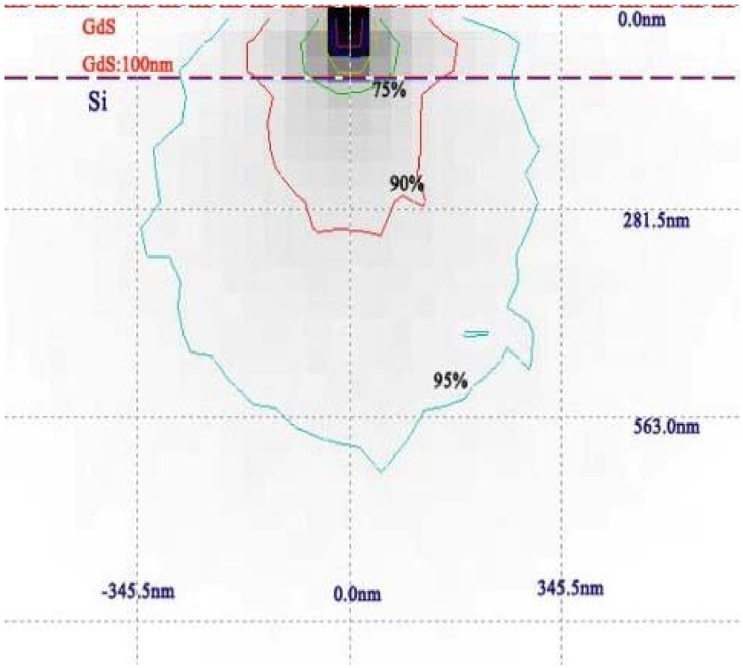
Radial Peak Shift under tensile and compressive strain

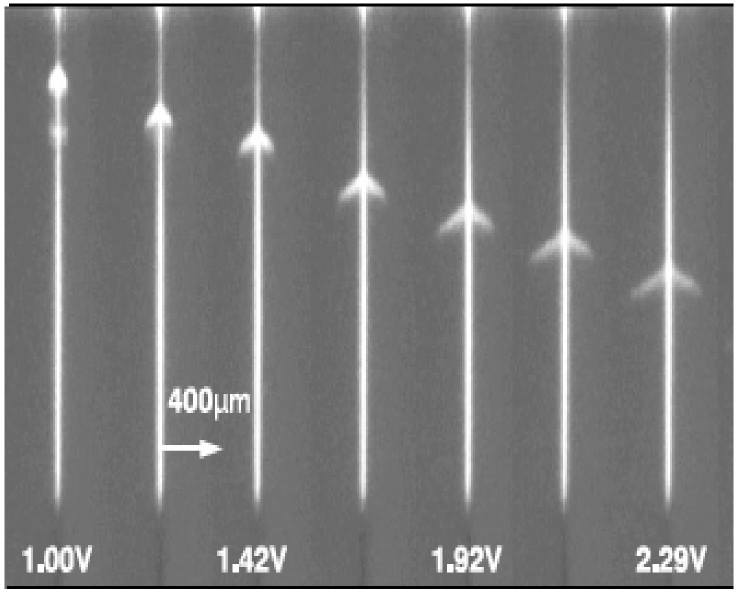


Radial Peak Shift under tensile and compressive strain



Scan step under consideration of resolution





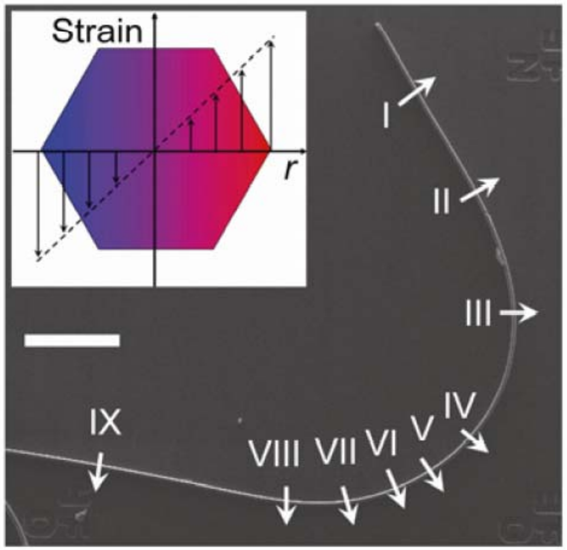
Diffusion of electrons

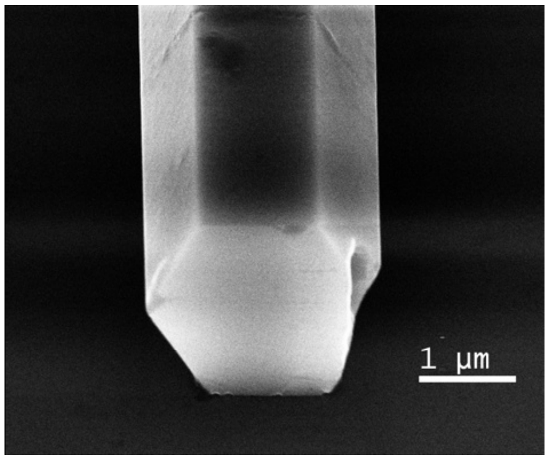
Electron beam: < 1 nm

Diffusion Length of exciton

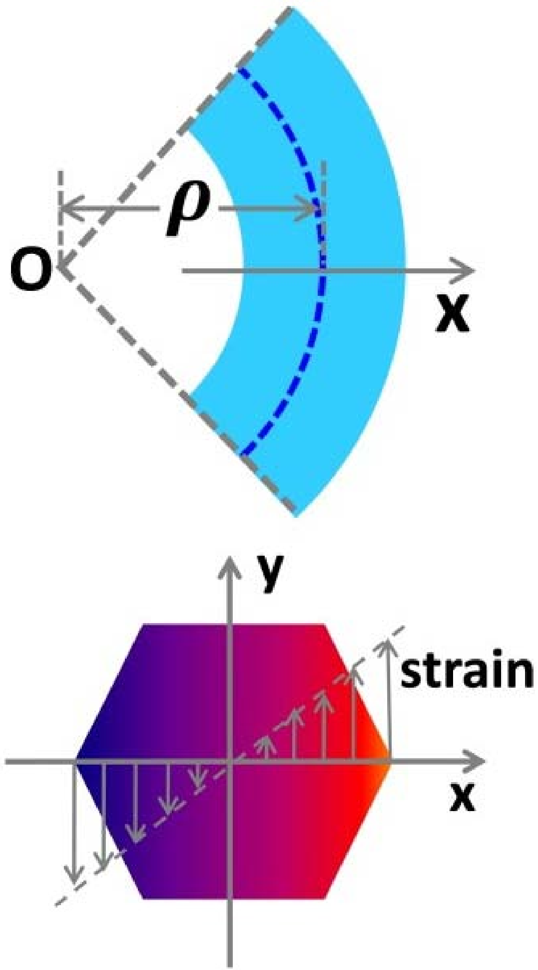
Scan step: 100 nm

Radial Peak Shift under free bending
Strain-Gradient Effect

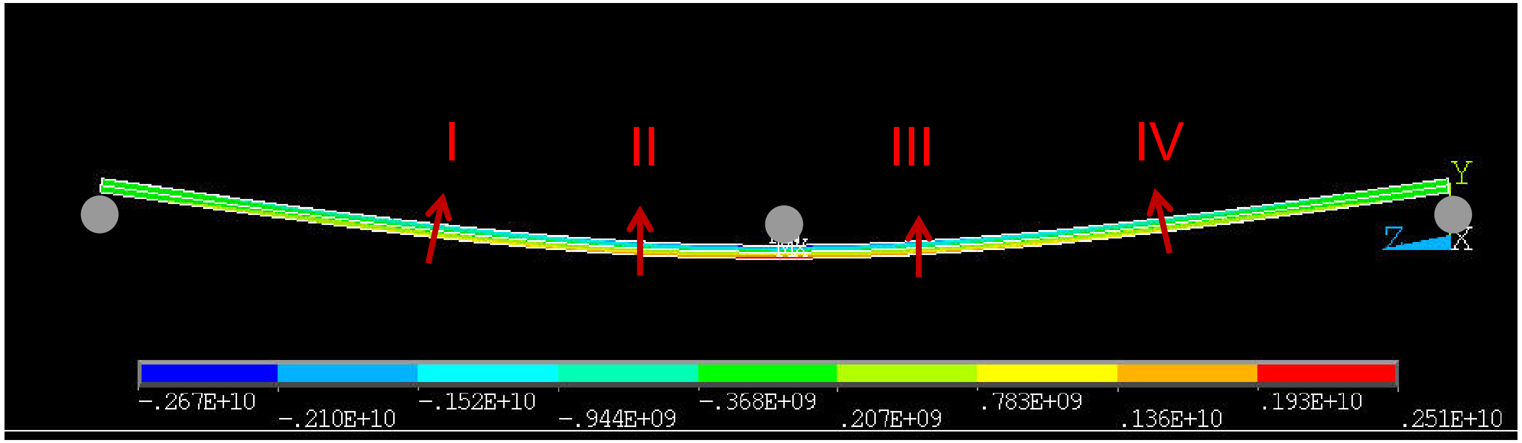


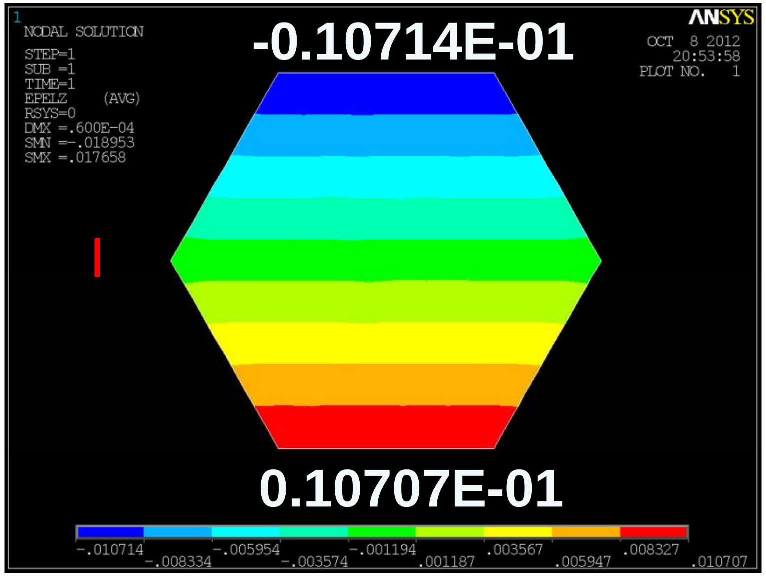


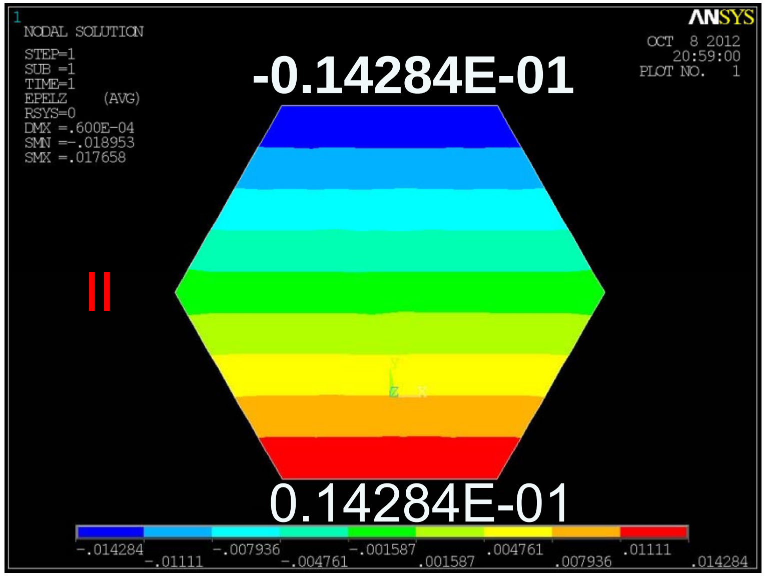
Scan step: 100 nm



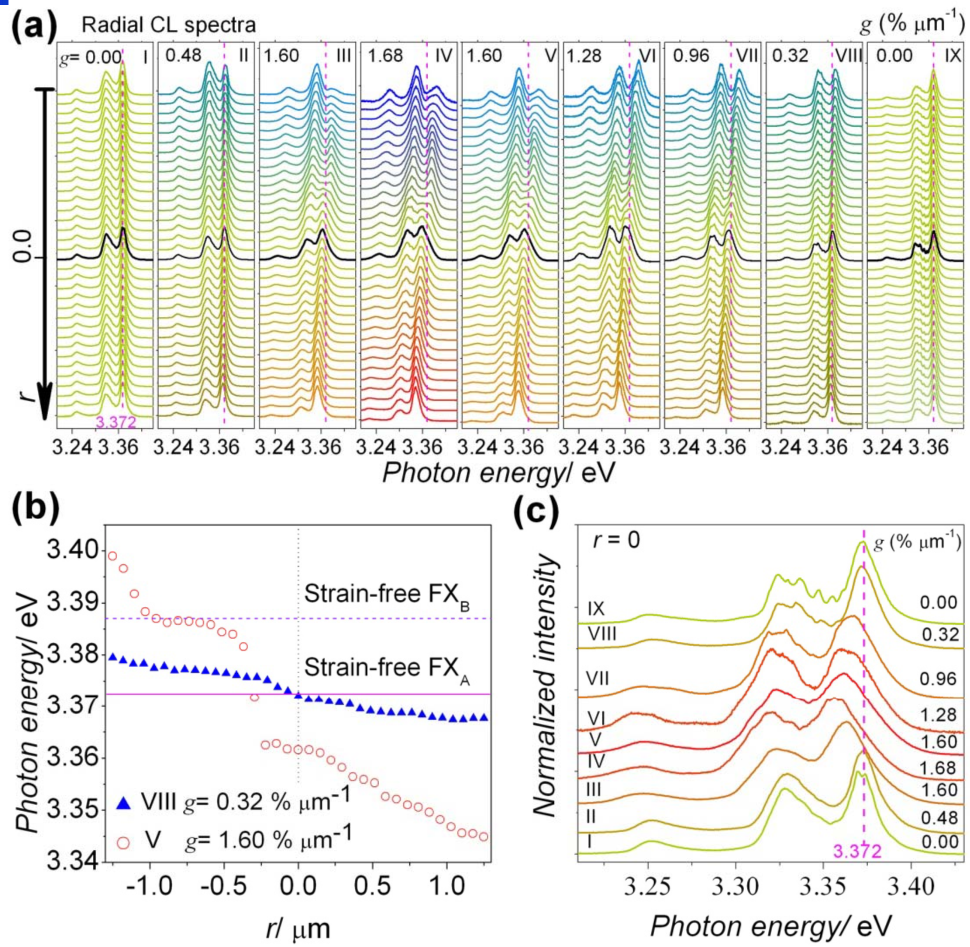
Simulation of the standard 3 point bending strain *d=2.0um*





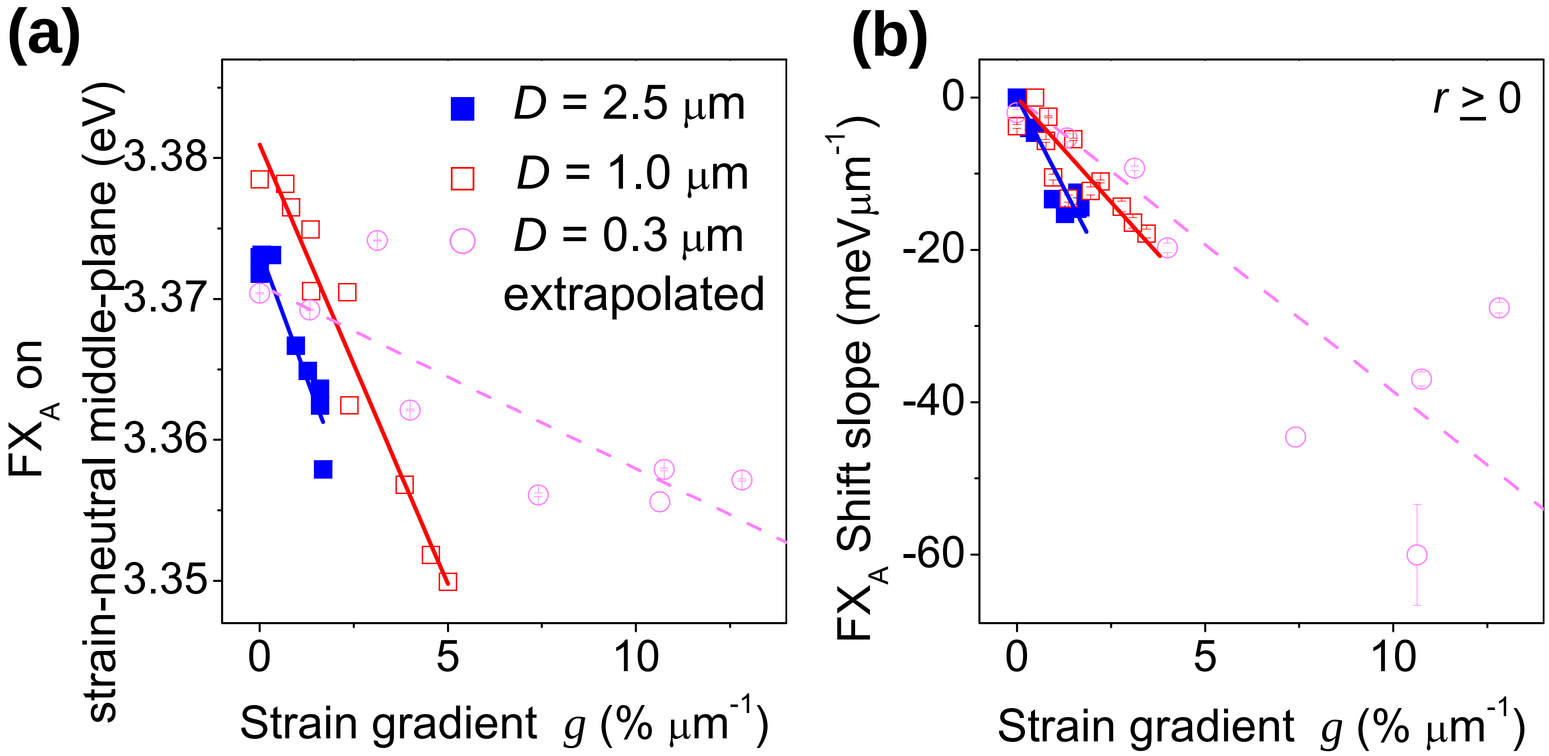


CL spectra at 81 K



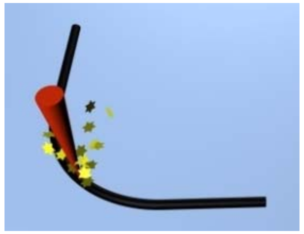
对应上图中各点做的横截面CL线扫描图谱。 紫色虚线代表无应变区域的CL峰的位置。蓝色、红色曲线分别代表在压应变、张应变端部出现的蓝移和红移．黑色实线代表中性面对应的CL谱。

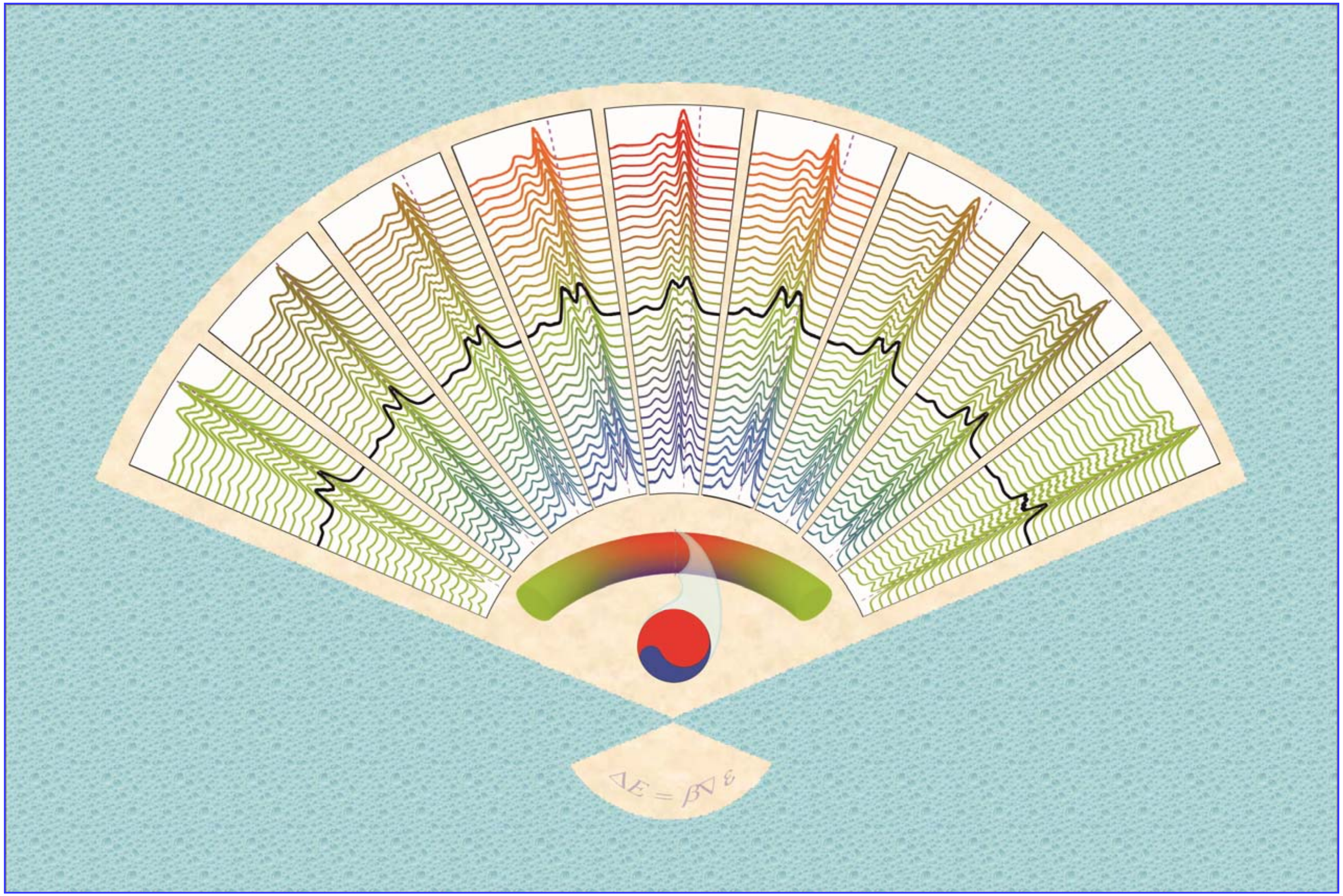
Peak Energy vs Strain gradient



(a) 、FXA Peak~ Strain gradient at the neutral plane;

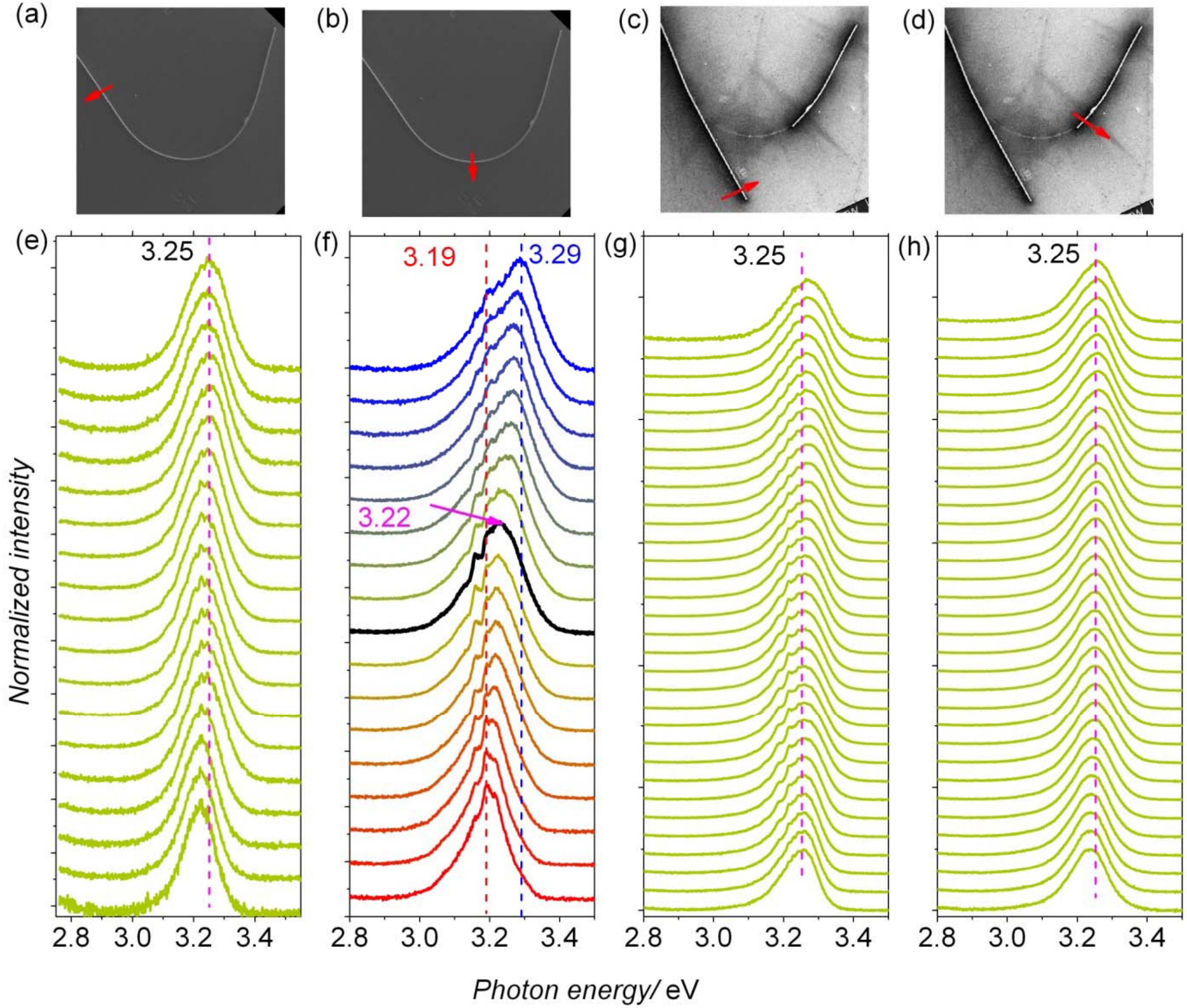
(b) 、 FXA Peak~ Strain gradient at the tensile side.



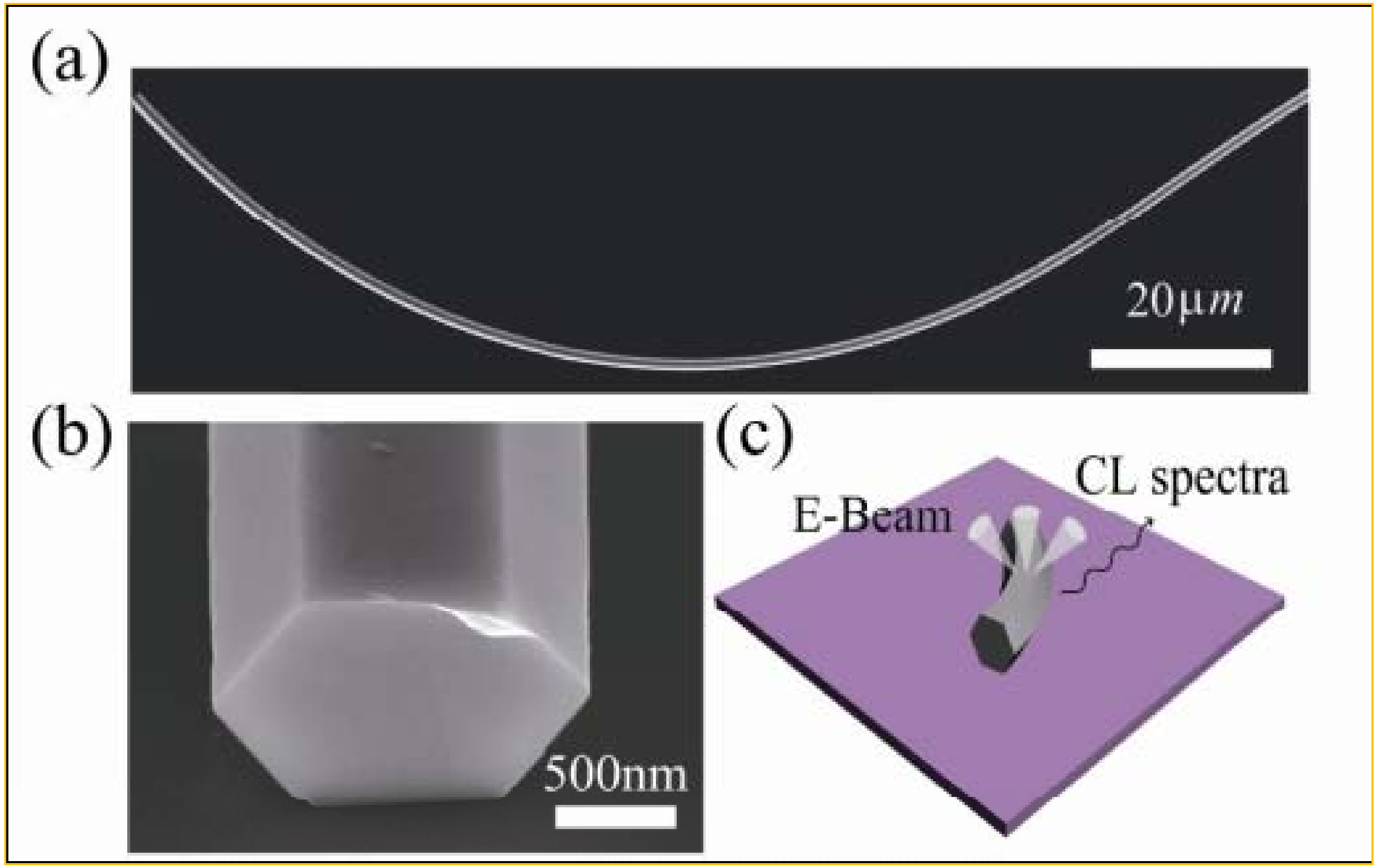


X. B. Han (韩晓冰) et al., Advanced Materials 24, 4707, 2012

Recover of the peak shift after strain release



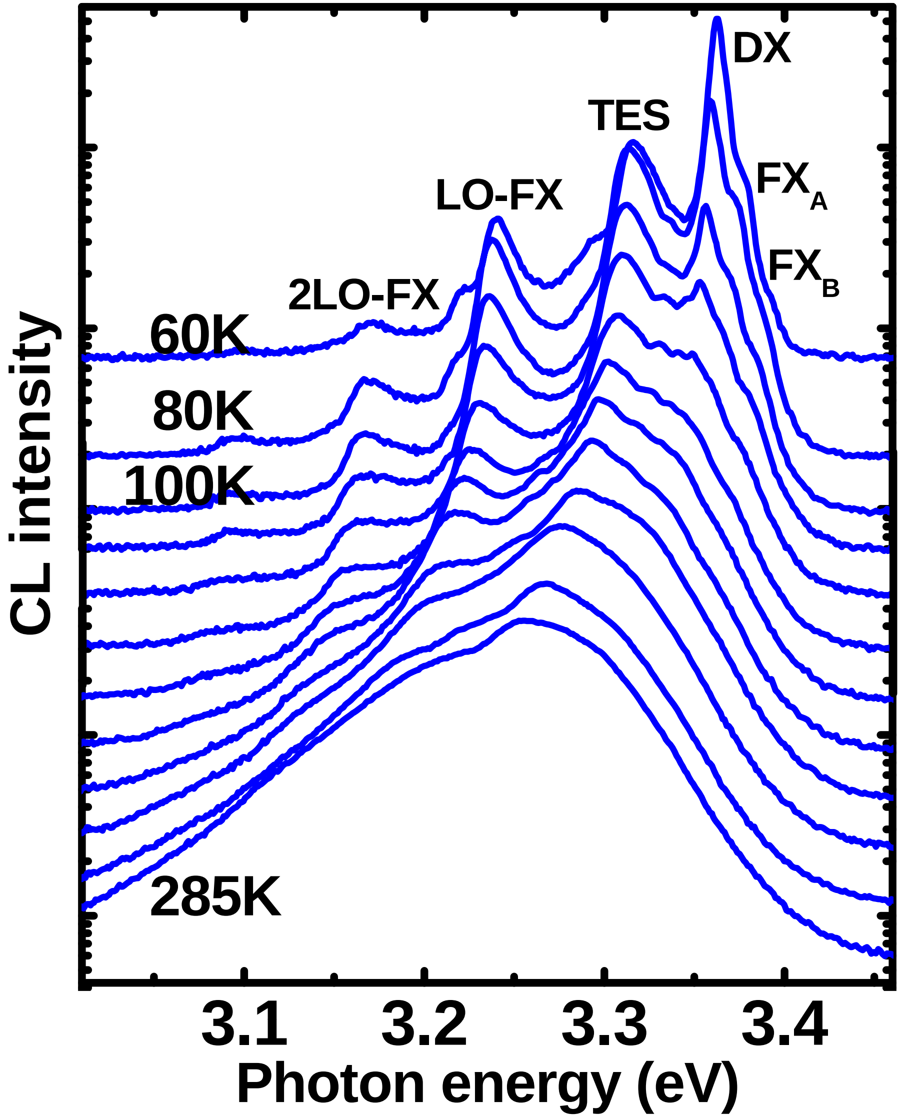
Strain induced exciton fine-structure splitting and shift in bent ZnO microwires

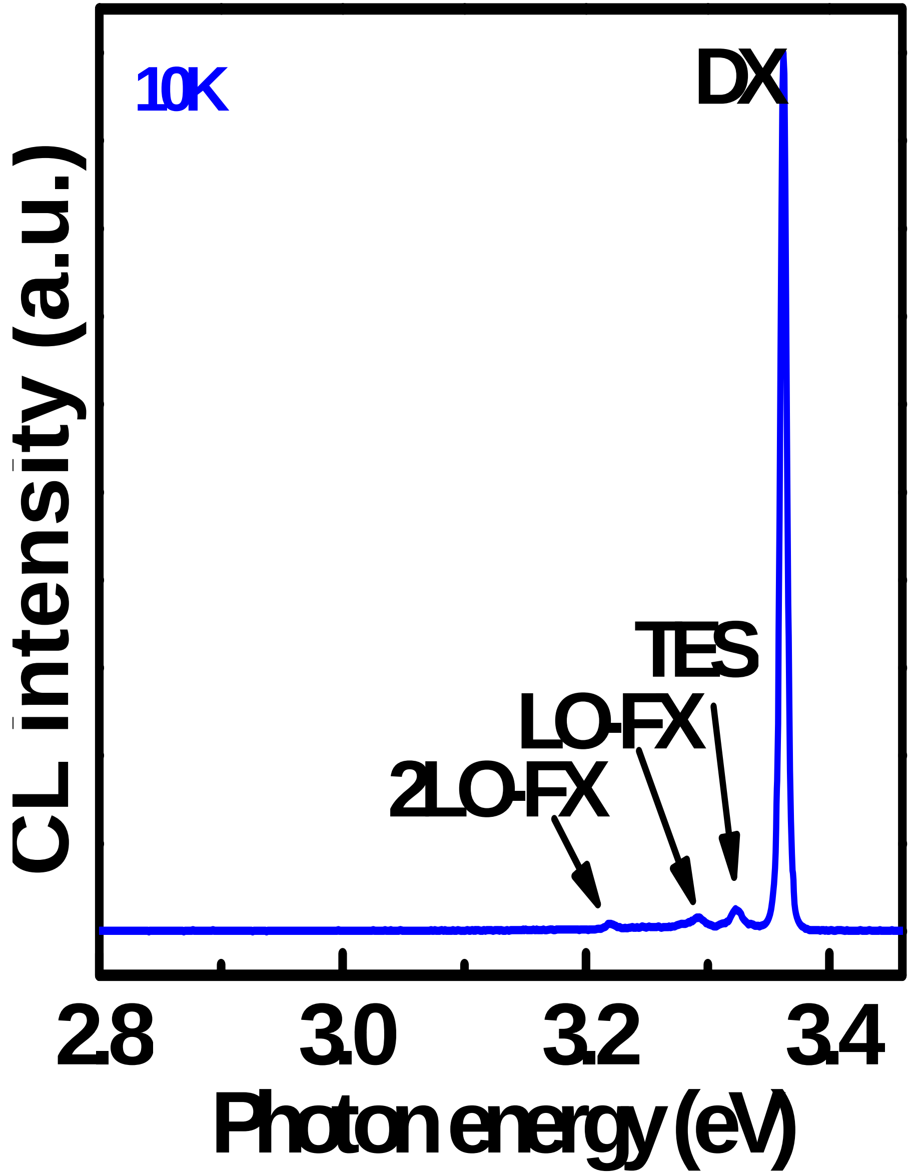


SCIENTIFIC REPORTS | 2 : 452,2012； Nature Publishing Group

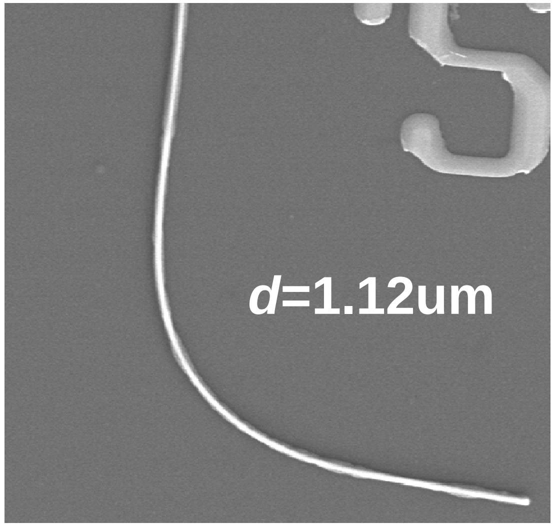
www.nature.com/scientific reports

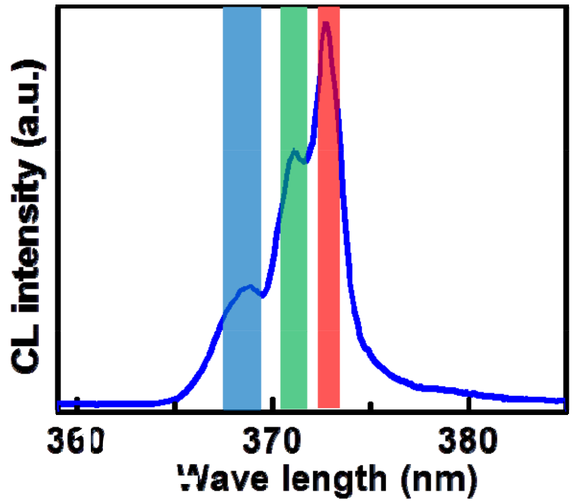
T-dependend CL spectrum

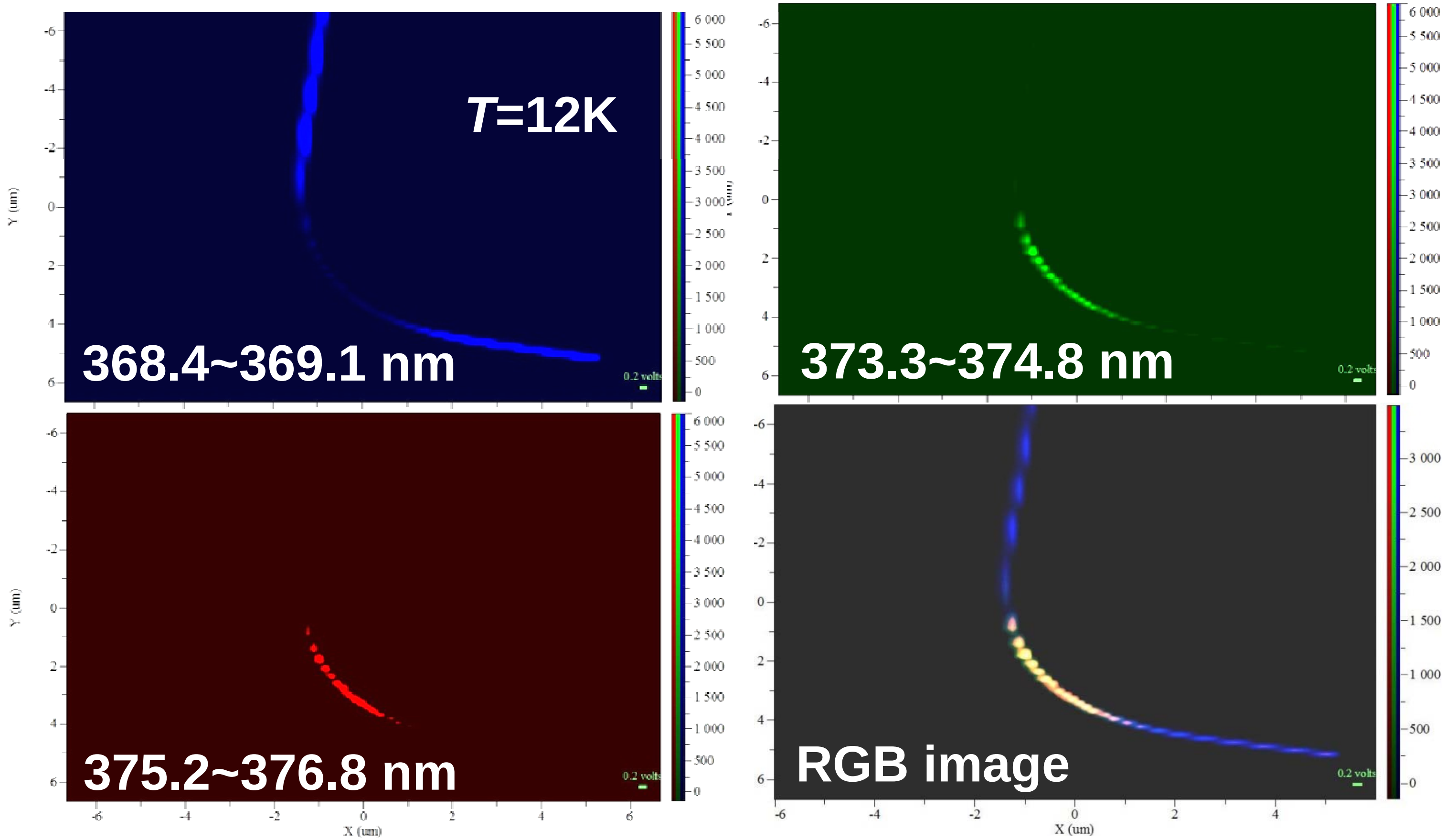




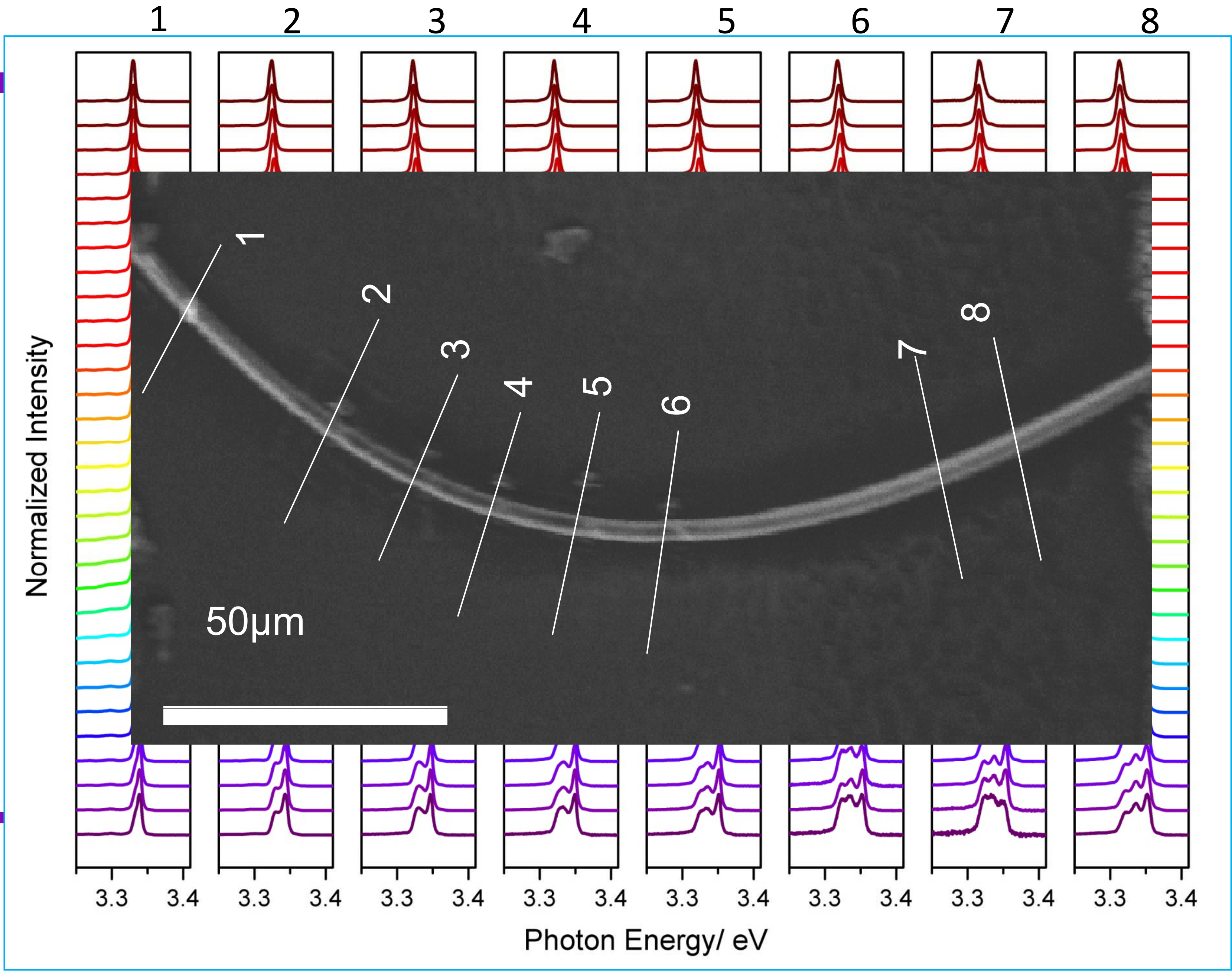
CL Mapping at different wavelength



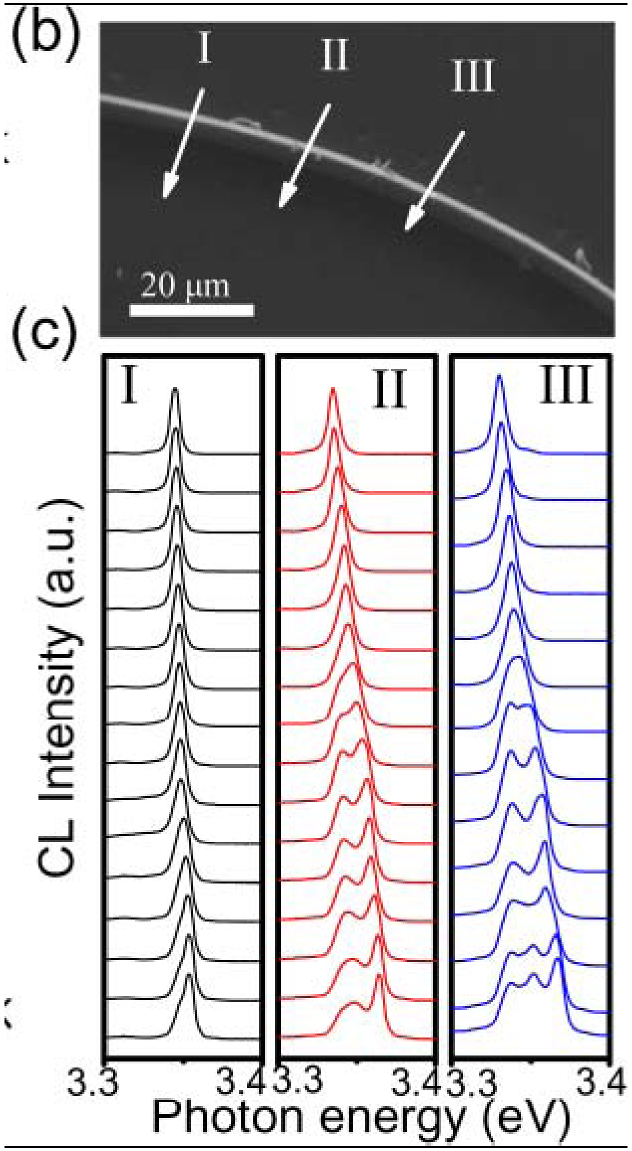


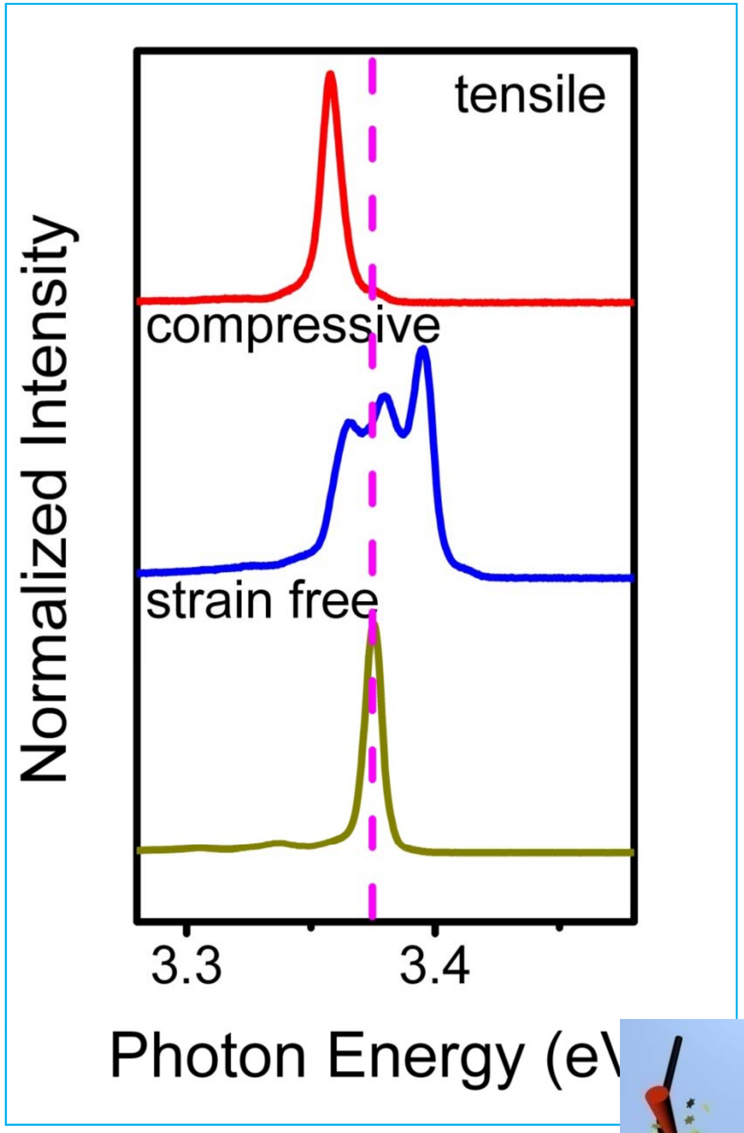


Systematic Shift and Splitting (strain)

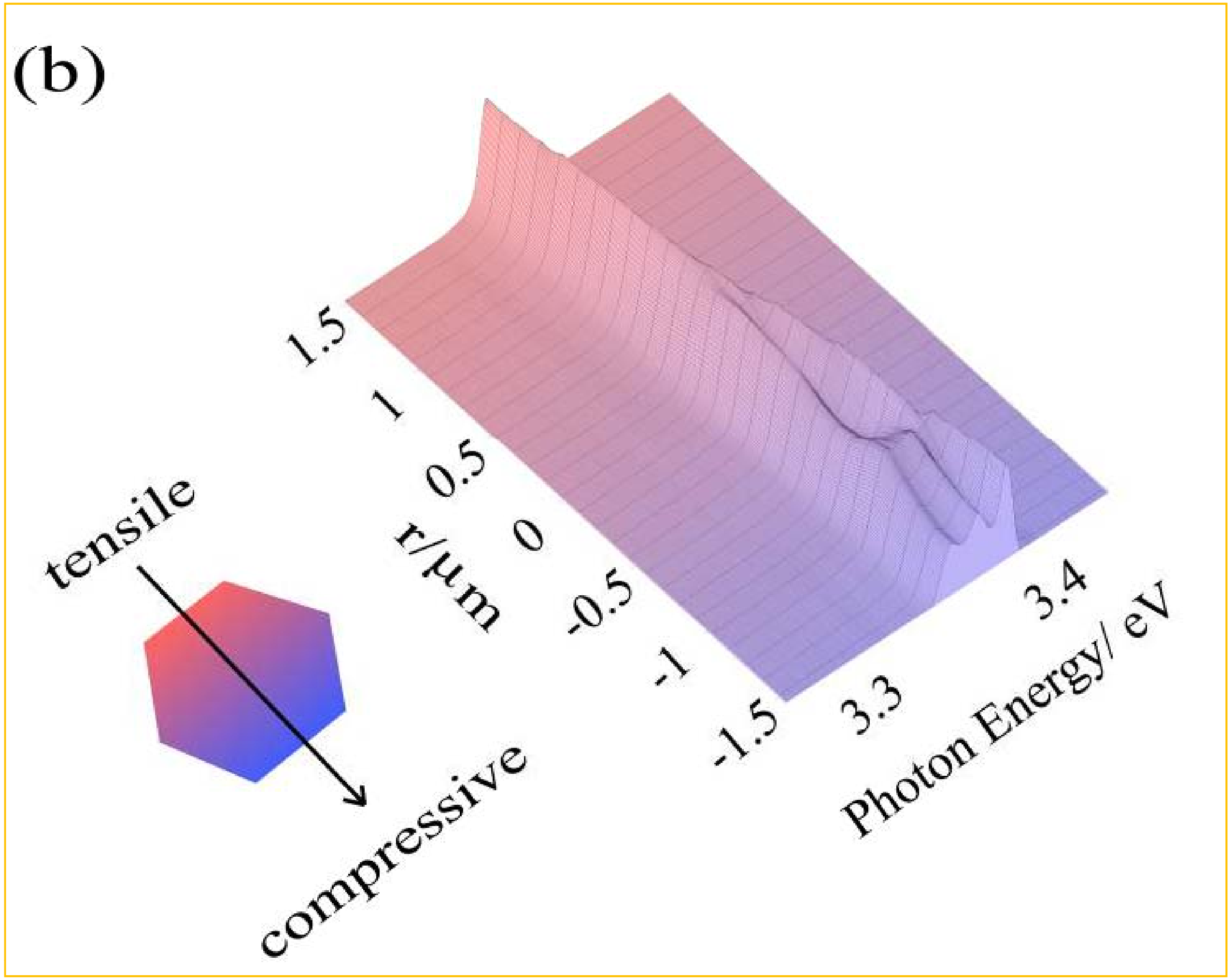


Systematic Shift and Splitting (strain)

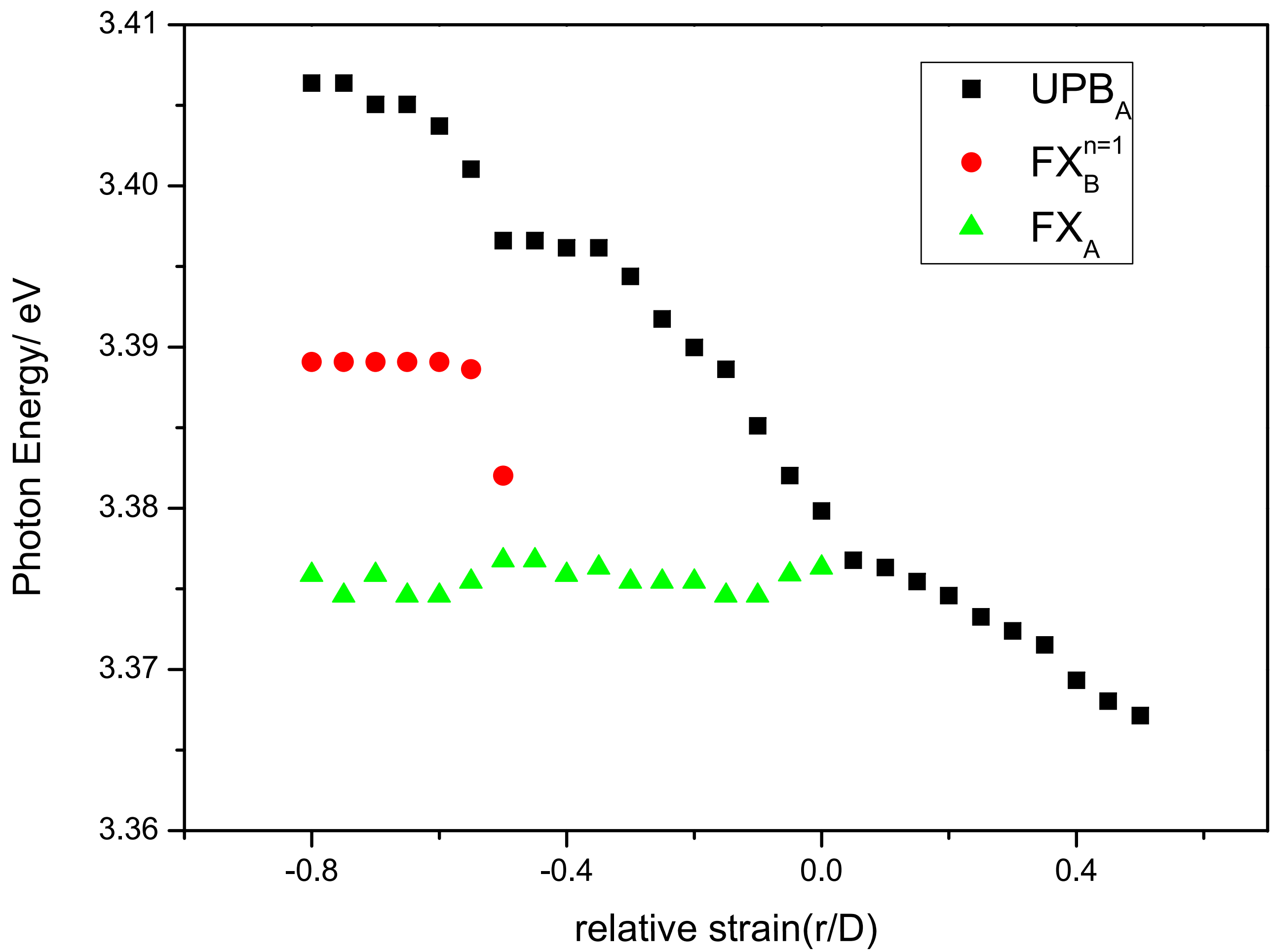




Systematic Shift and Splitting (strain)

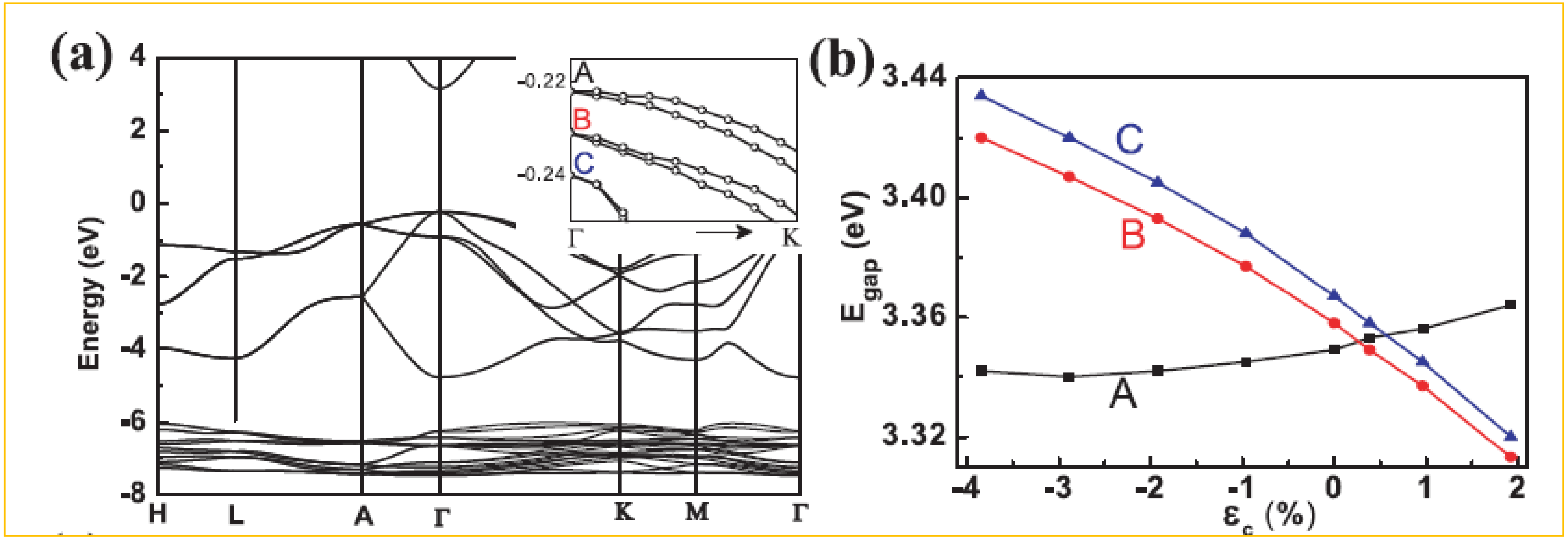


Systematic Shift and Splitting



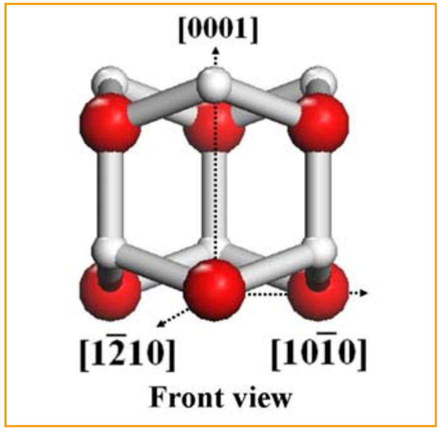
Scientific Reports 2， 452, 2012; Nature Publishing Group

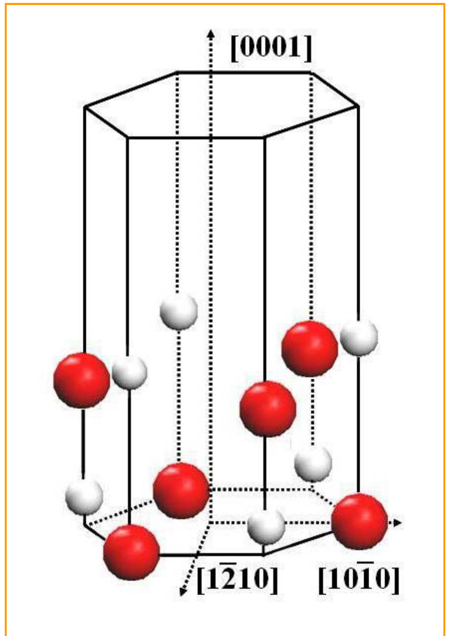
Strain induced valence band splitting

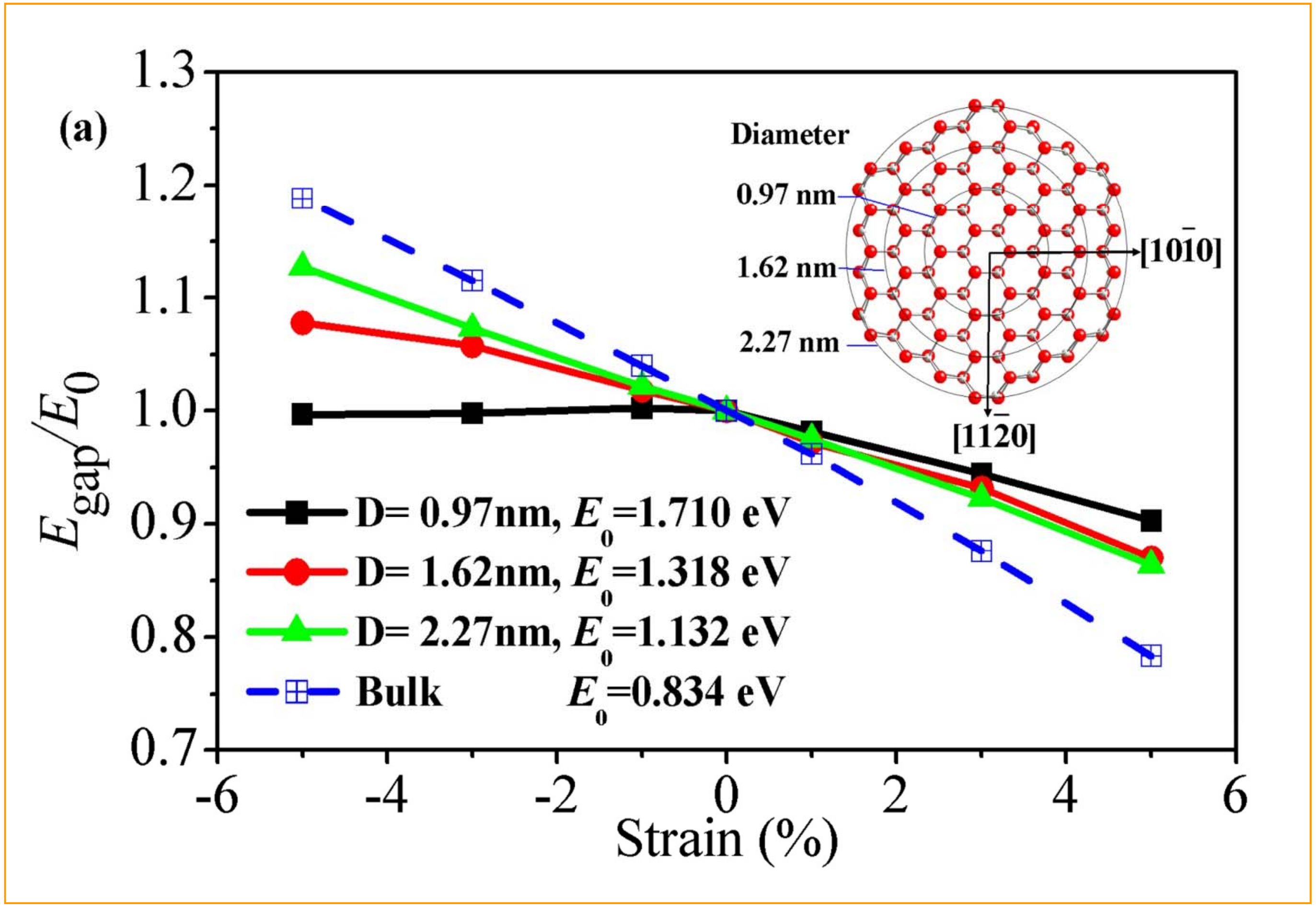


Lattice distortion induced crystal field deformation which causes the valence band splitting

Strain induced Band Gap Change







Xiaobing Han et al., Advanced Materials 21, 4937，2009

Summary

- ✓ Cathodoluminescence spectroscopy is a very useful technique for precise and delicate characterization in nanostructures
- ✓ High spatial resolution of the CL enables us to correlate the finest modification of the strain effect in semiconductor nano/microwires.

Thank you So much!