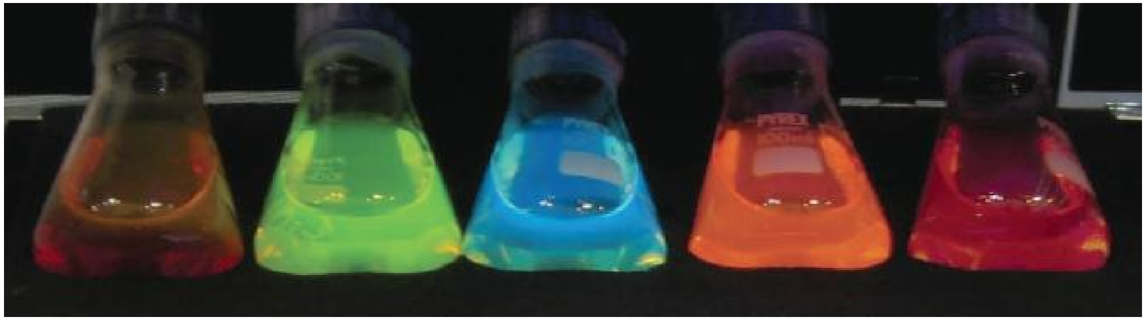
MANCHESTER
1824

The University of Manchester

Making and Using Nanoparticles



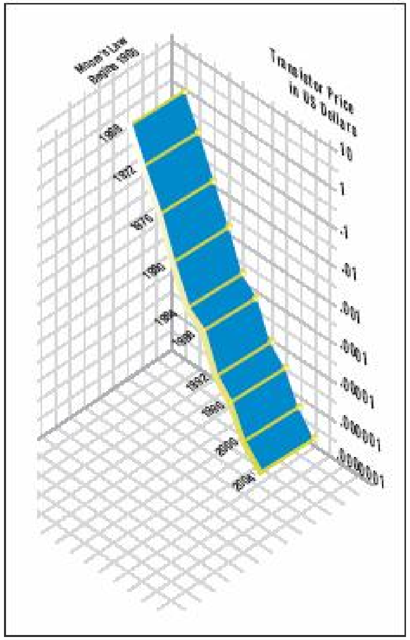
Paul O'Brien

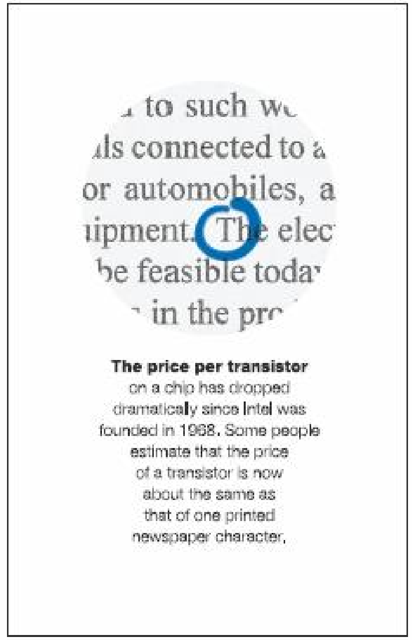
The School of Chemistry

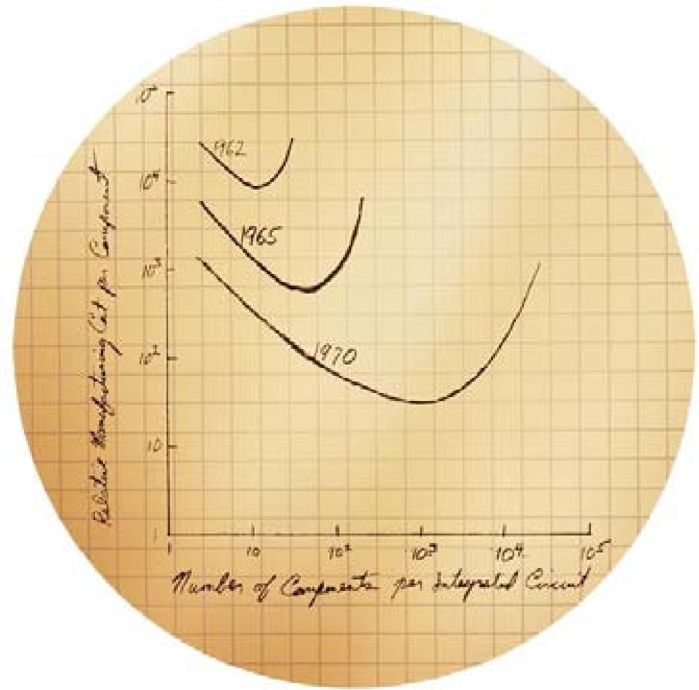
and The Manchester Materials Science Centre

Structure of Talk

- Why now ?
  - Looking at some nanodimensional objects by way of introduction
- Synthetic approaches semiconductors
- How nanoparticles grow and rods and tetrapods
- Other materials a rogues gallery
- What are some of the opportunities
  - The Nanoco Technologies Ltd perspective
- Closing remarks







Electronics, Volume 38, Number 8, April 19, 1965

Microprocessor	Year of Introduction	Transistors
4004	1971	2,300
8008	1972	2,500
8080	1974	4,500
8086	1978	29,000
Intel286	1982	134,000
Intel386™ processor	1985	275,000
Intel486™ processor	1989	1,200,000
Intel® Pentium® processor	1993	3,100,000
Intel® Pentium® II processor	1997	7,500,000
Intel® Pentium® III processor	1999	9,500,000
Intel® Pentium® 4 processor	2000	42,000,000
Intel® Itanium® processor	2001	25,000,000
Intel® Itanium® 2 processor	2003	220,000,000
Intel® Itanium® 2 processor (9MB cache)	2004	592,000,000

350 nm

250 nm

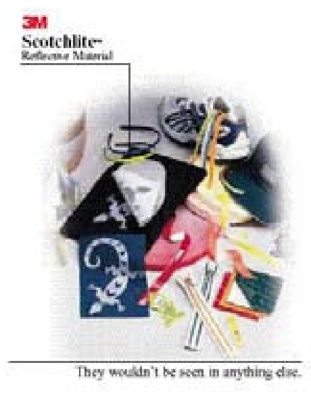
180 nm

What are lost dimensions?

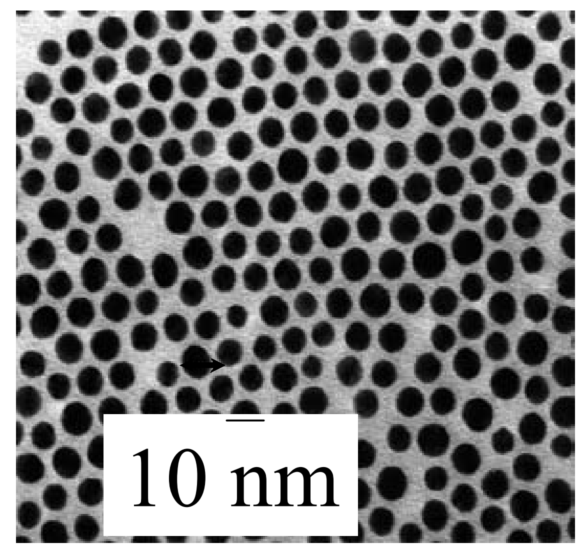
Industrial Development and a History of Precise Size Control

1850

1980

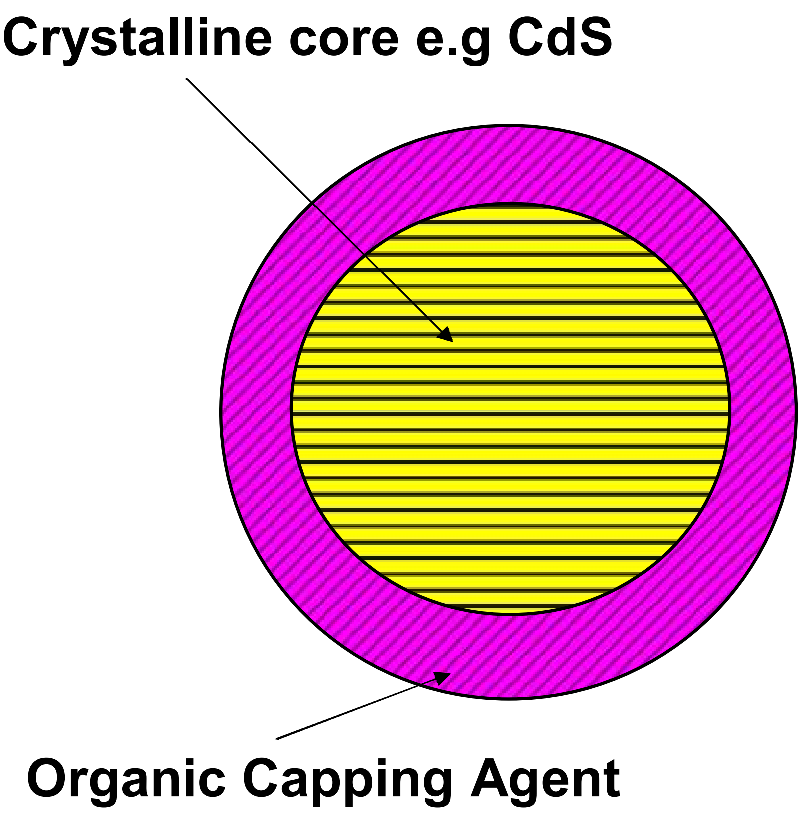


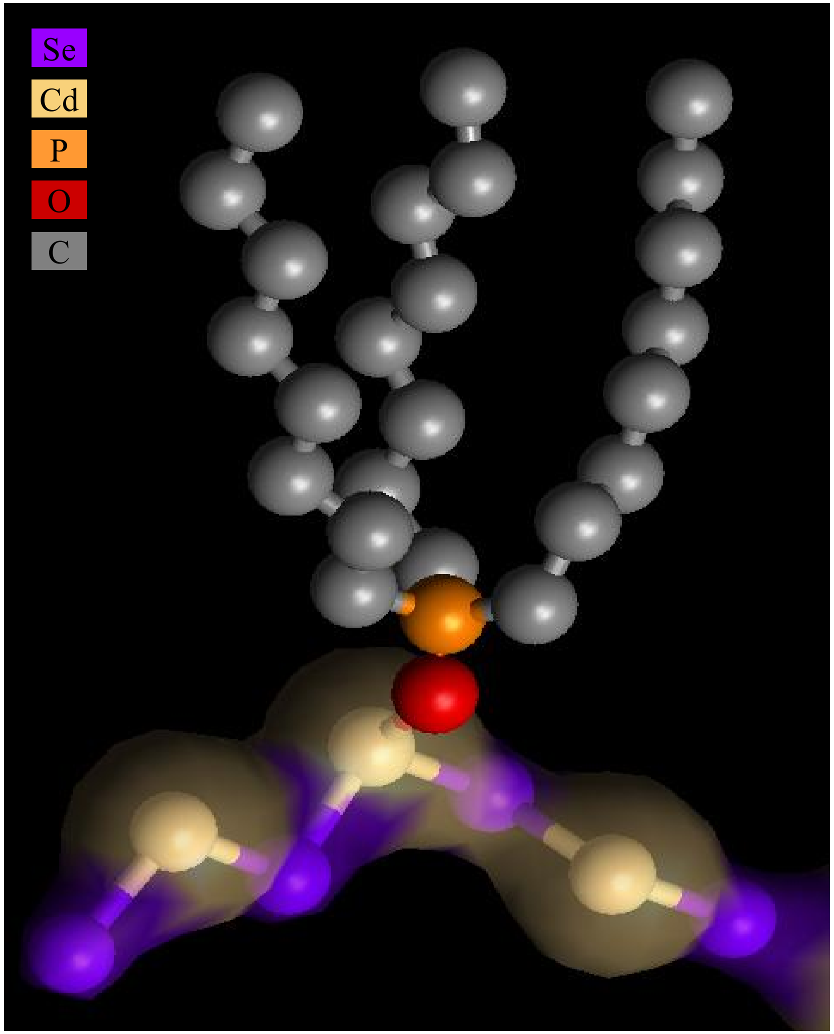
2004



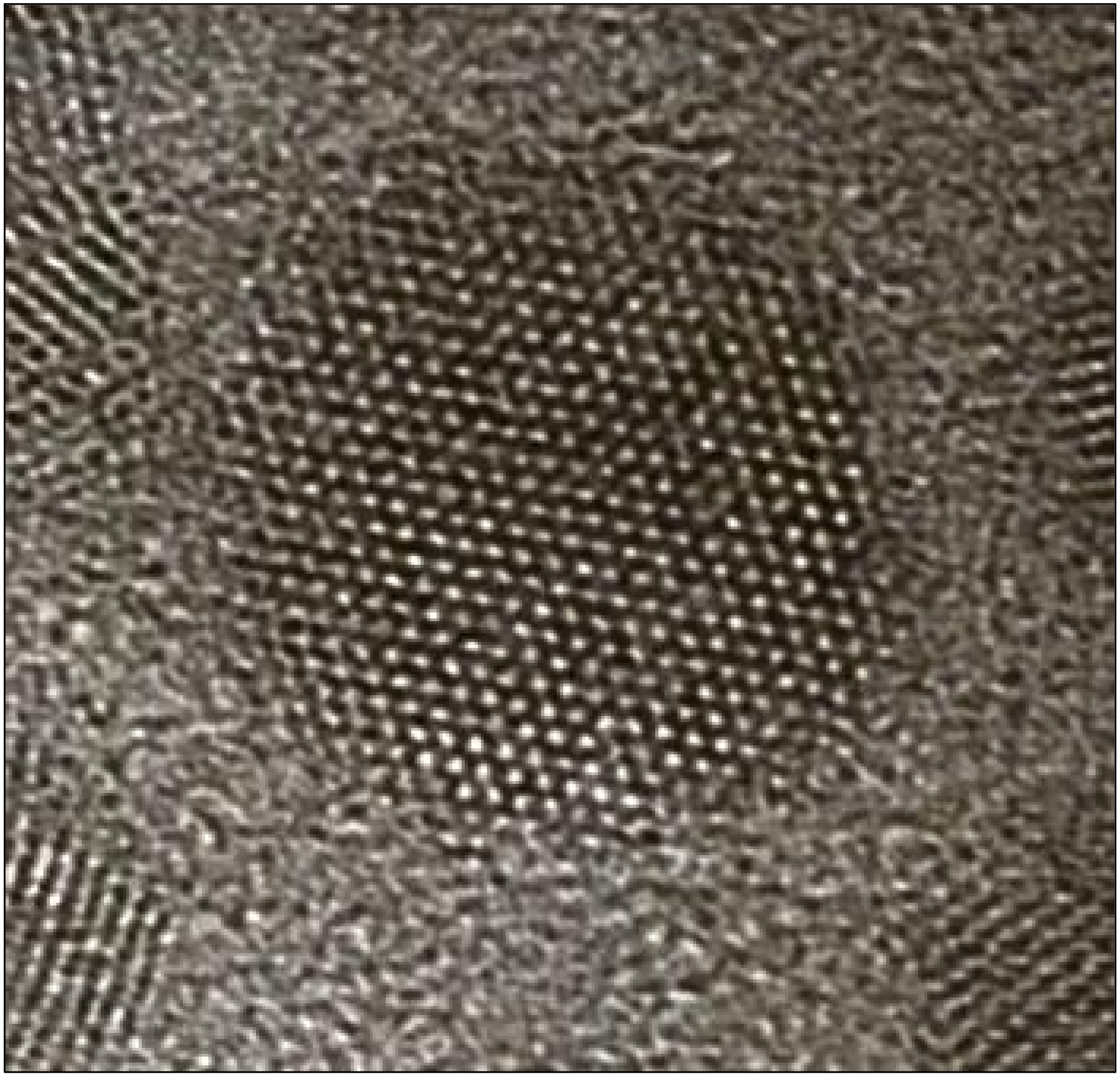
Ball Bearings for the 21st Century!

Quantum Dot and nano Particle Structures I



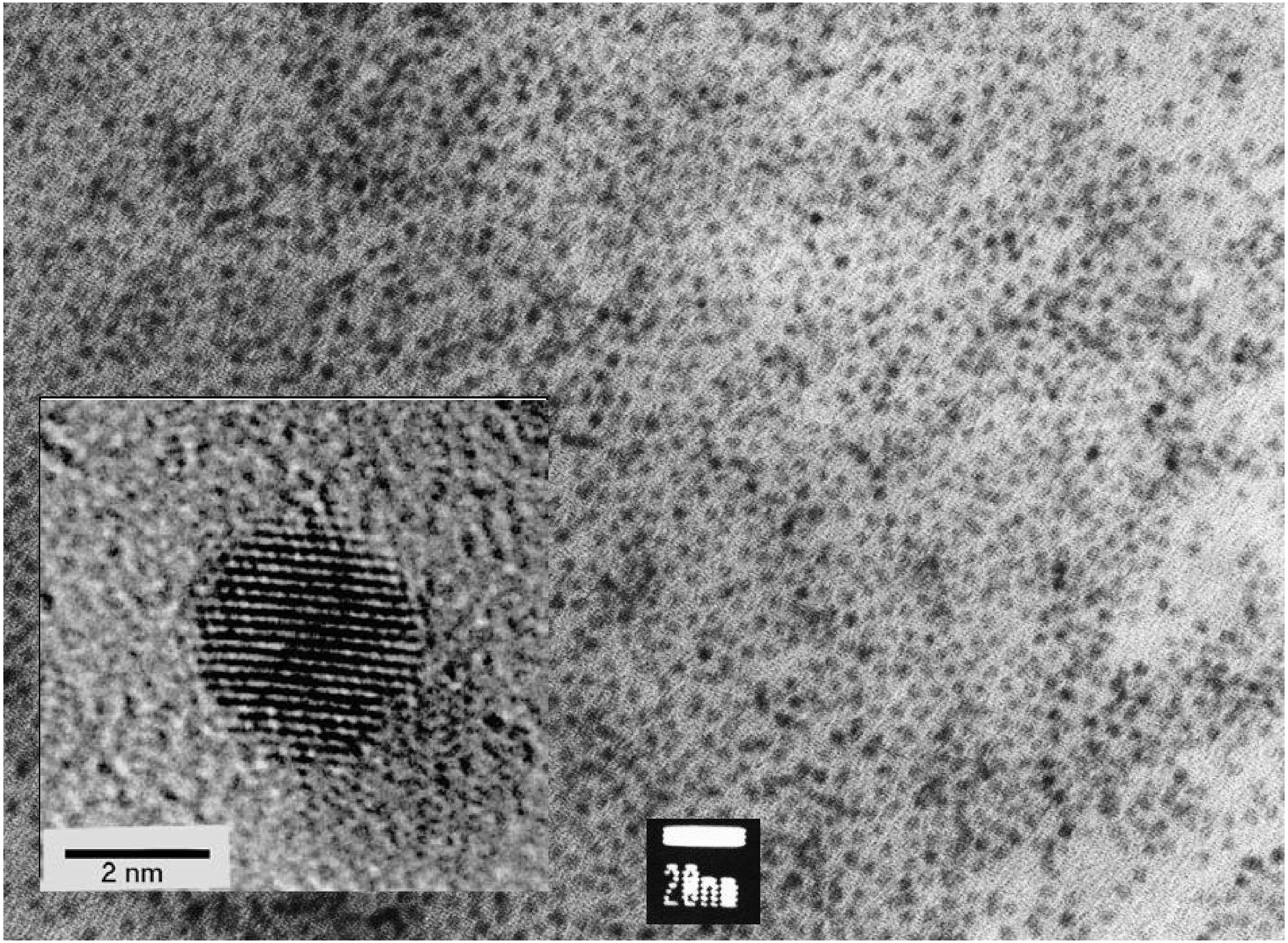


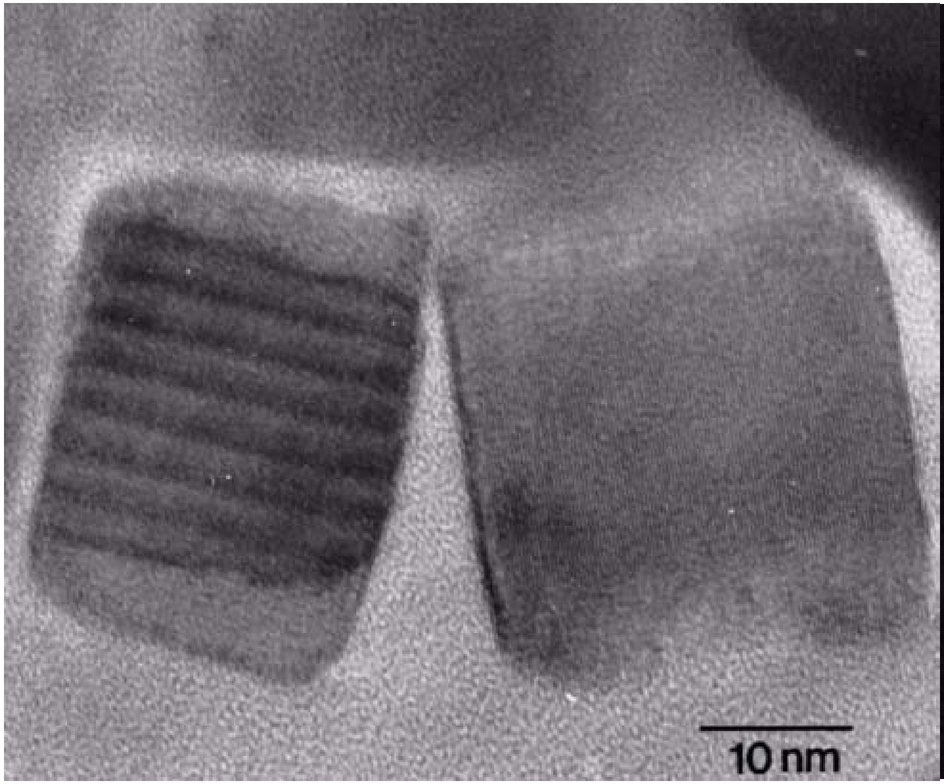
‘Metal Organic Dot’

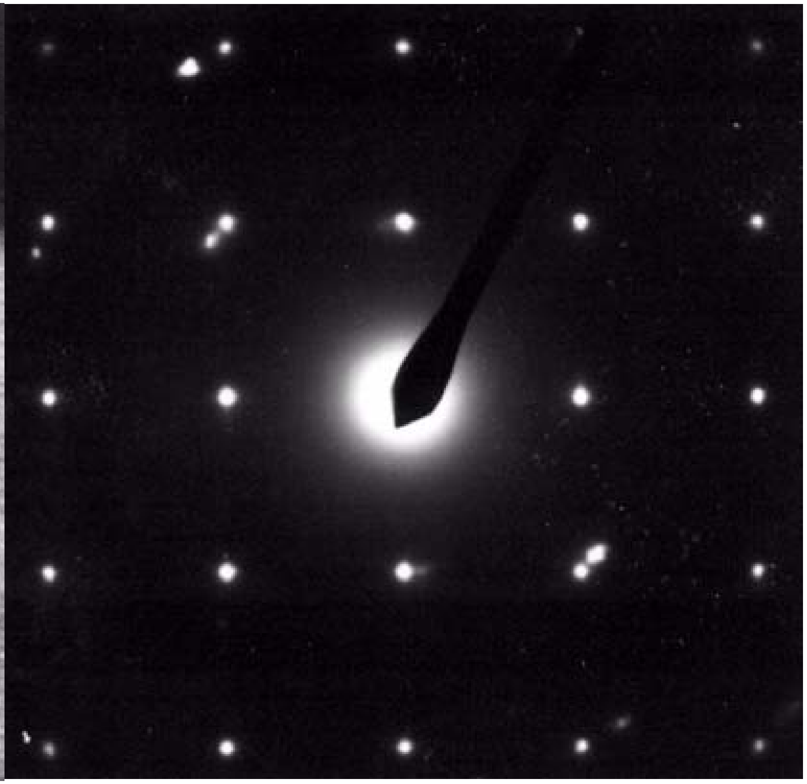


Chem Commun., 1999, 1573-1574

More CdSe



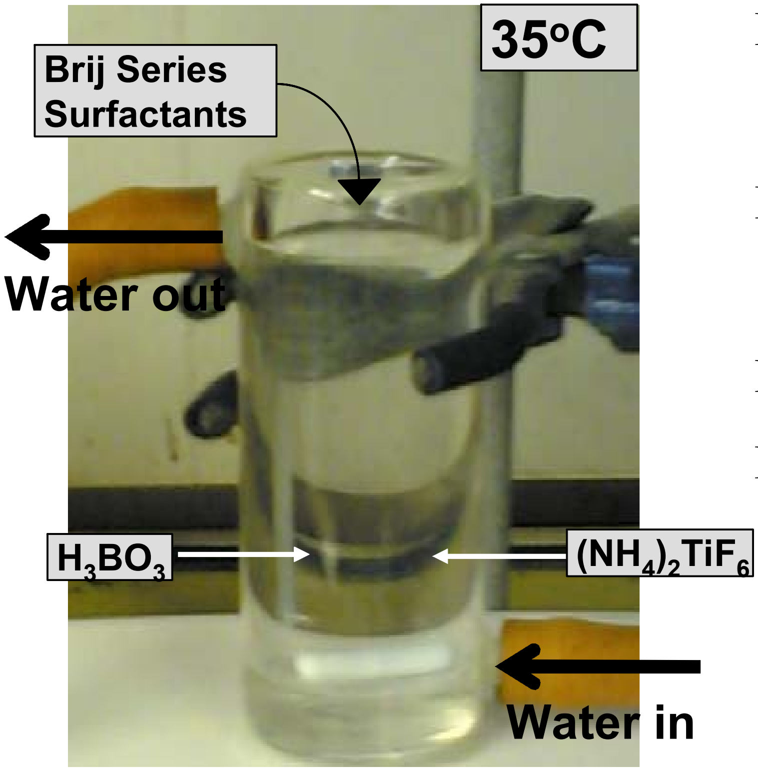




Sample of PbS Coated with TOPO

J. Materials Chemistry, 1997, 7, 1011

Uniform Microscopic NH_4TiOF_3 or TiO_2 Mesocrystals by a Room Temperature Self-assembly Process



Schematic of Experiment

Incomplete hydrolysis of Ti complex:

$$[TiF_6]^{2-} + nH_2O \rightleftarrows [TiF_{6-n}(OH)_n]^{2-} + nHF \ (n \leqq 3)$$

Formation of NH_4TiOF_3:

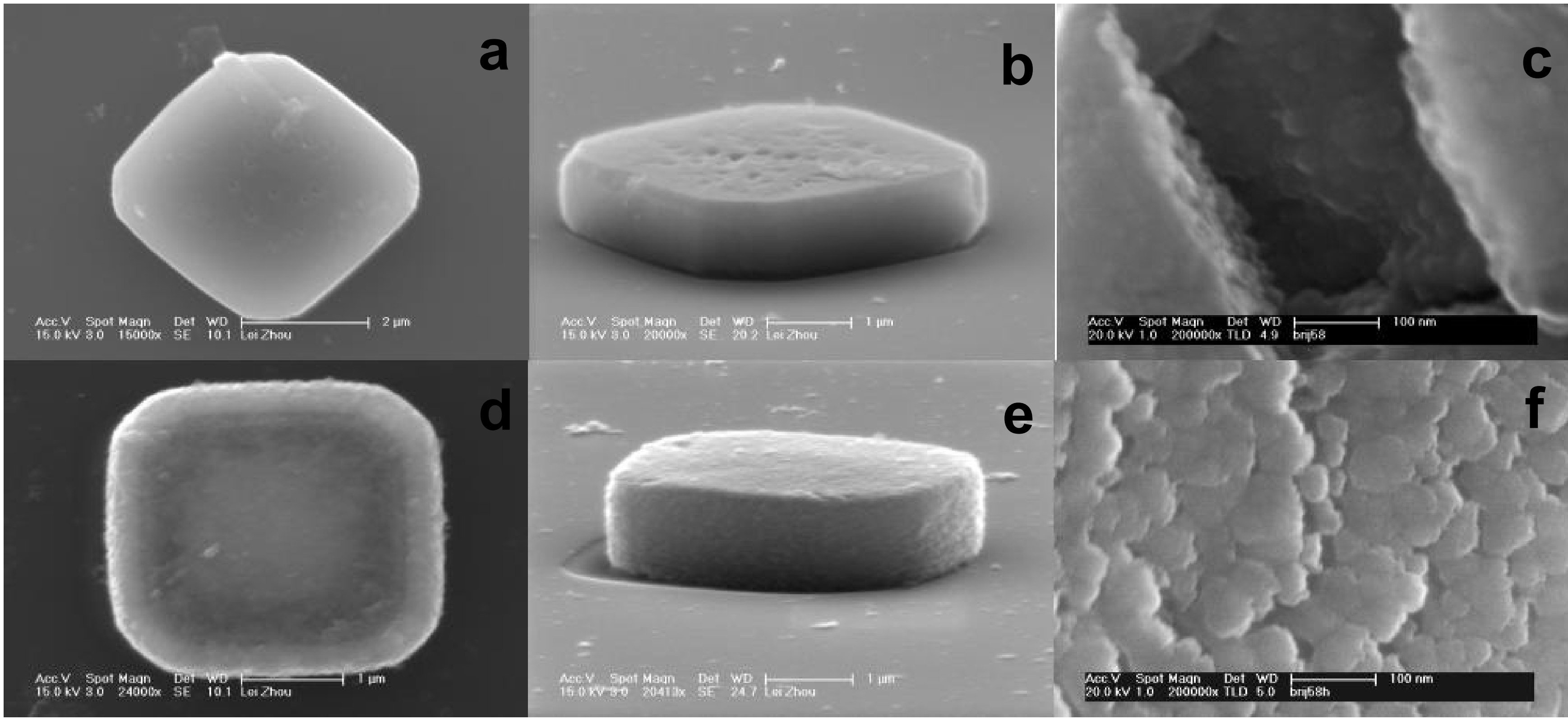
$$[TiF_3(OH)_3]^{2-} + H^+ + NH_4^+ \rightarrow NH_4TiOF_3\downarrow + 2H_2O$$

Removal of HF:

$$H_3BO_3 + 4HF \rightarrow HBF_4 + 3H_2O$$

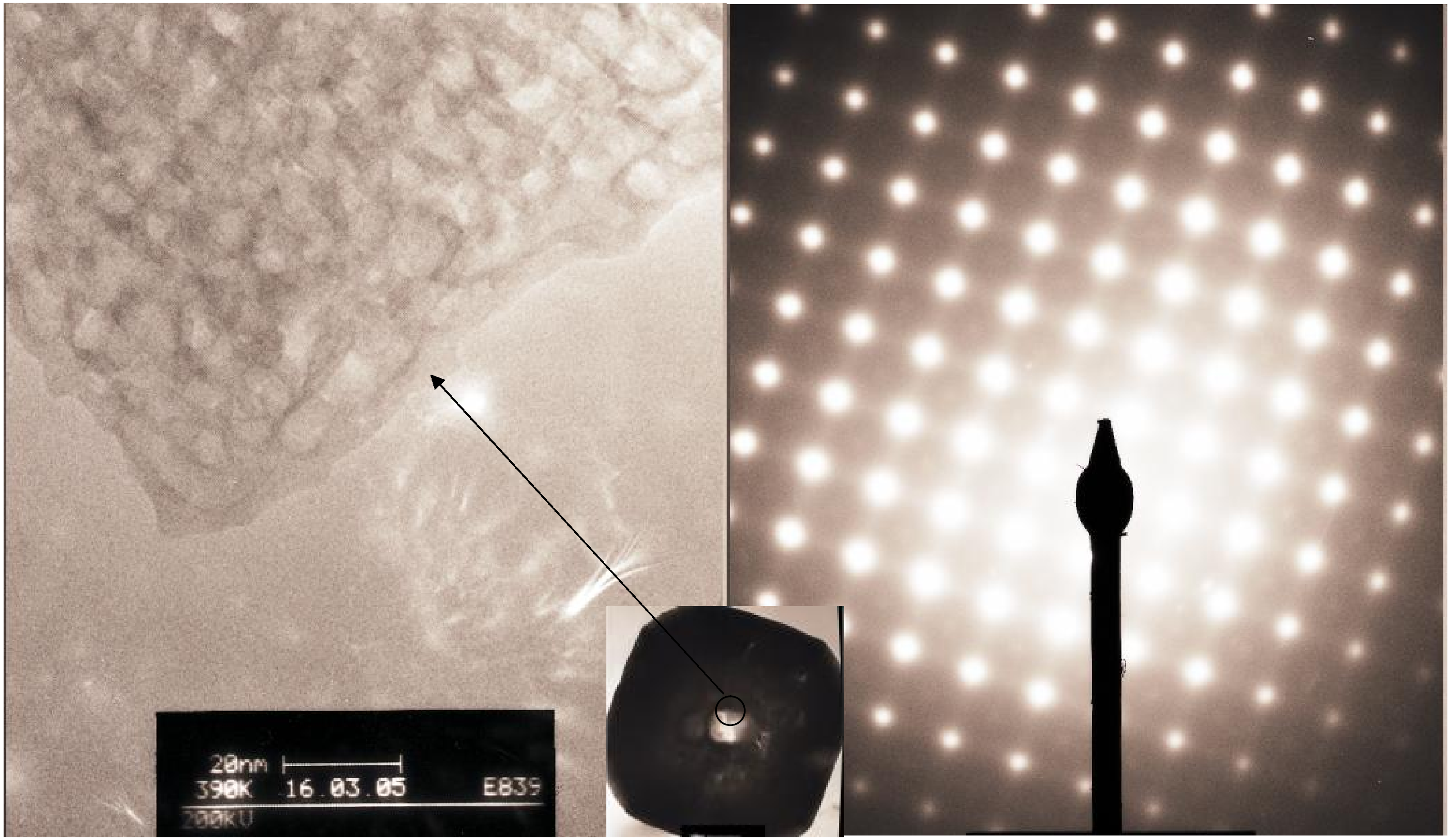
e.g. 15 g of Brij 58 is added into the 50 ml bath solution containing $(NH_4)_2TiF_6$ (0.1 $mol\cdot dm^{-3}$) and H_3BO_3 (0.2 $mol\cdot dm^{-3}$).

Impact of sintering $[NH_4][TiOF_3]$ to TiO_2



SEM images of samples before and after sintering. a, b, top view and cross-section of an as-prepared sample. c, ultrahigh resolution image of a broken point. d, e, top view and cross-section of after a sintered sample. f, ultrahigh resolution image of surface .

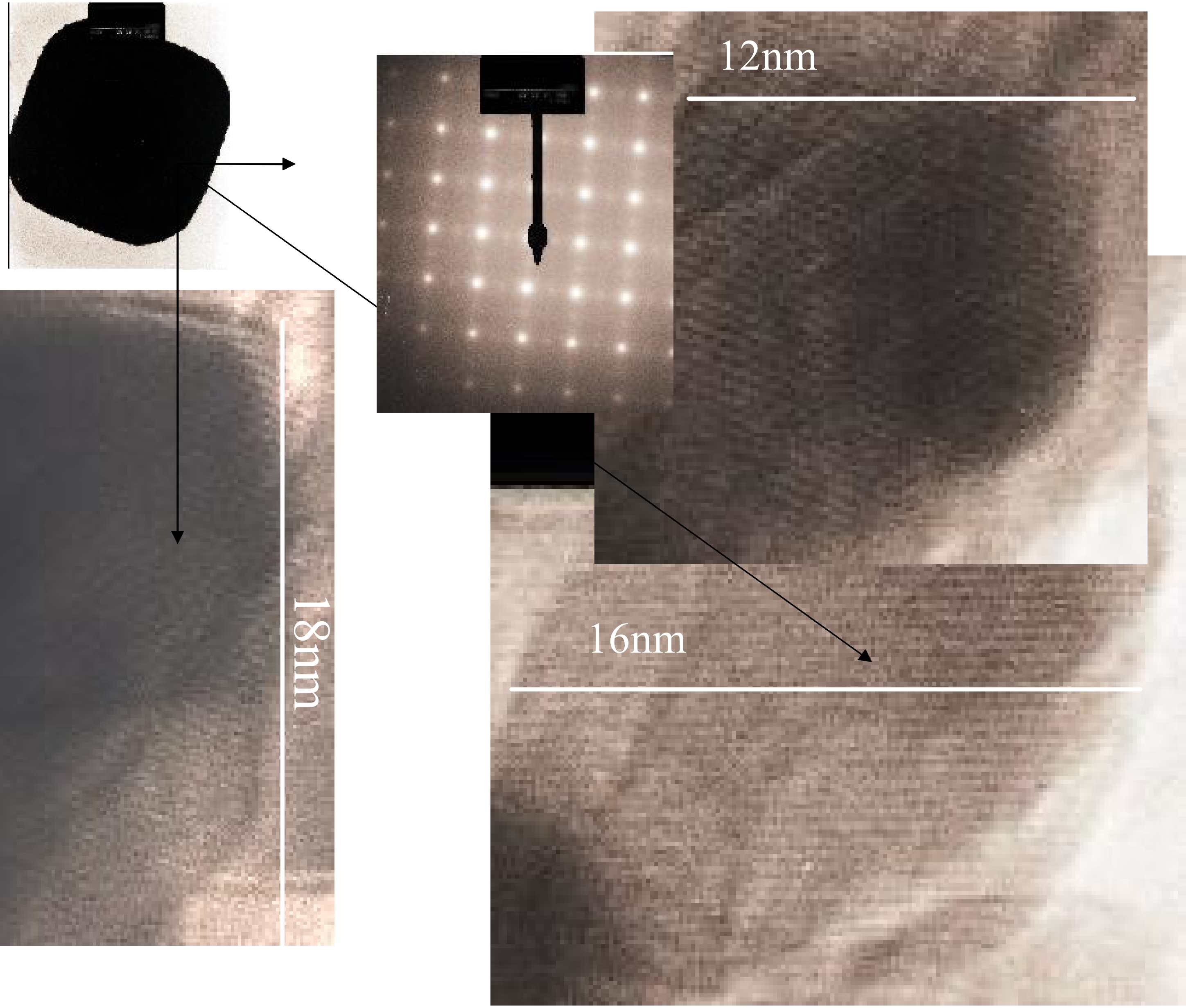
TEM analysis of as-prepared samples



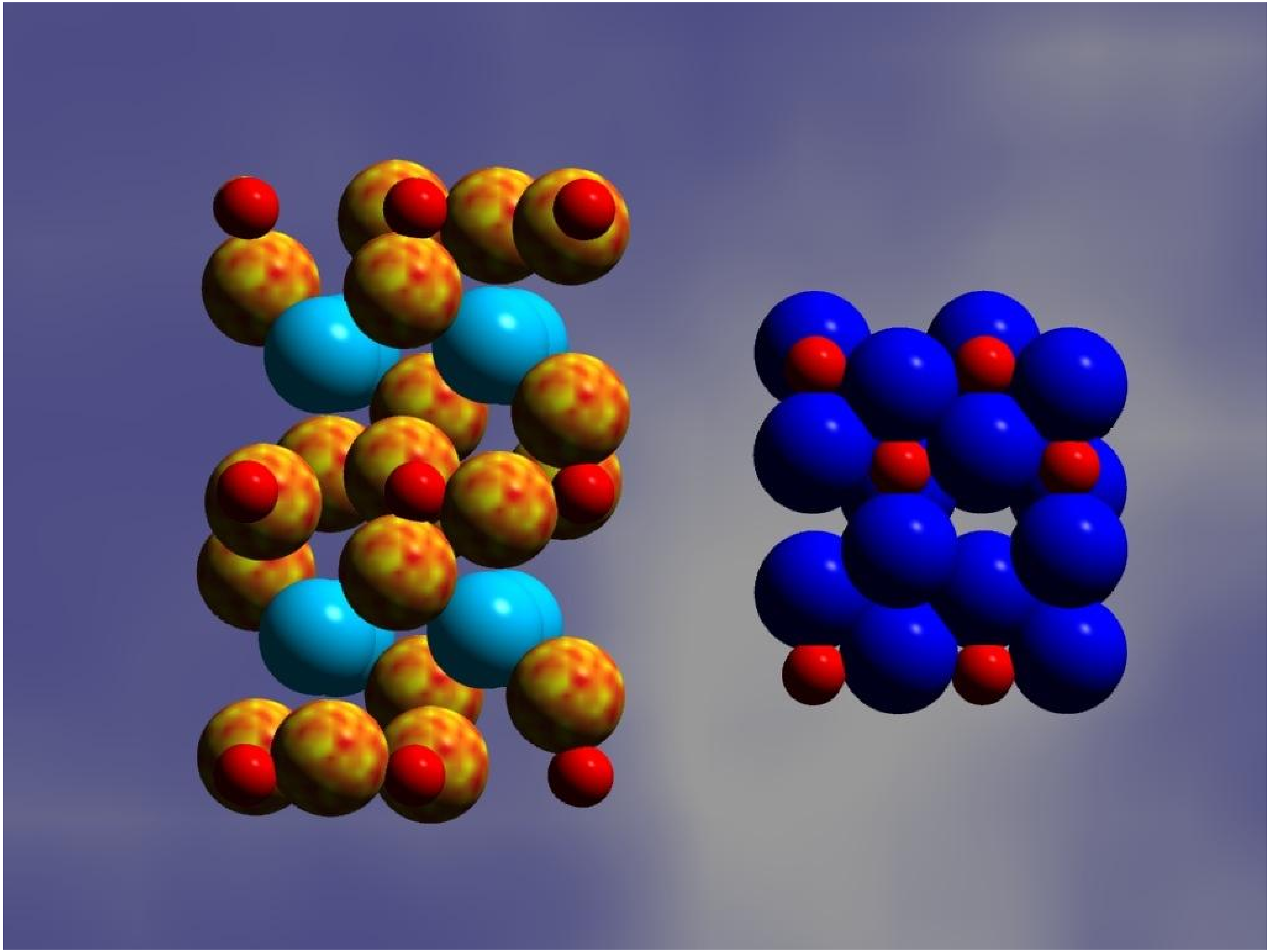
TEM images and SAED Pattern of as-prepared samples.

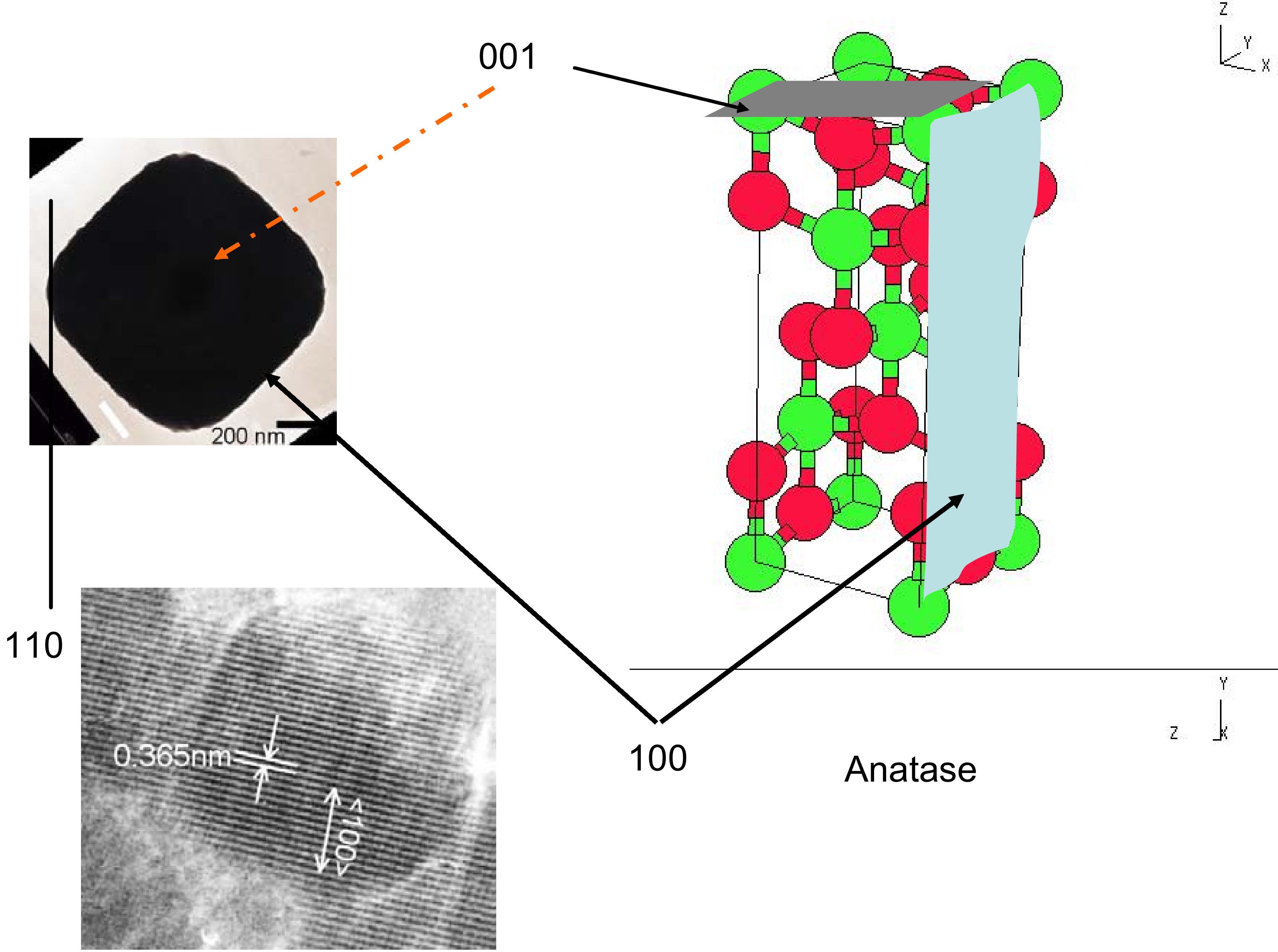
TEM:

Particles Prepared with 30% Brij58, after sintering



TEM videos of samples precipitated in presence of 23.1 wt% Brij 58 at 35 degrees centigrade for 20 hours




001
110
200 nm
0.365nm
<100>
100
Anatase
Z
Y
X

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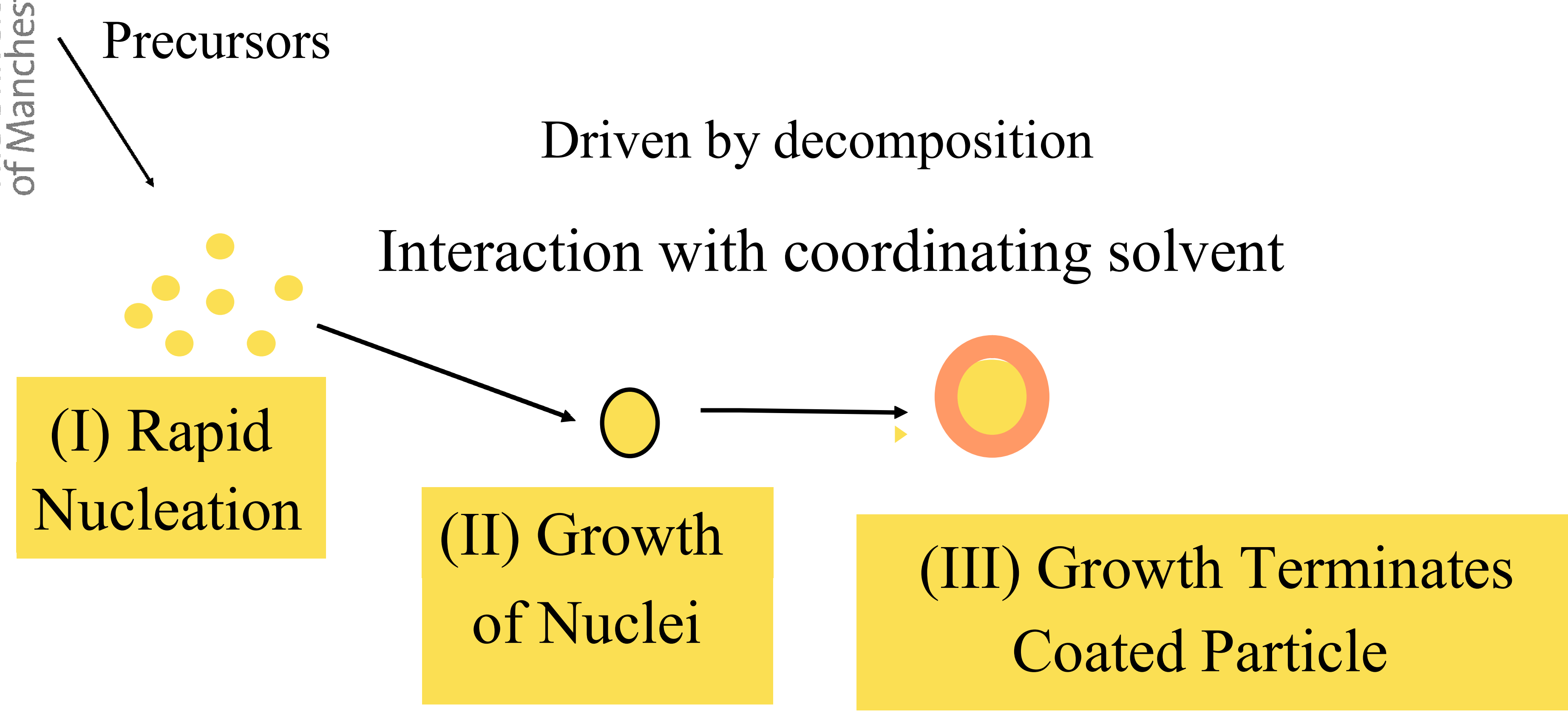
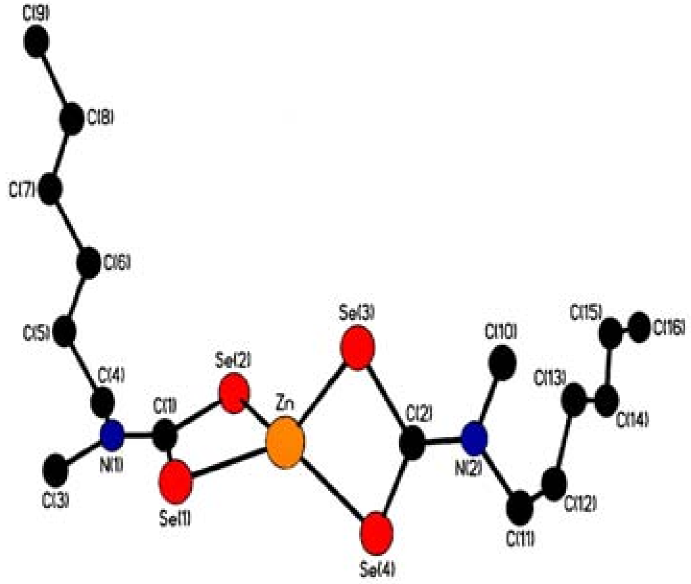


Requirements for Nanoparticulate Synthesis

. $Cd(Se_2CNRR')_2 \longrightarrow CdSe$

O'Brien et al Chem Comm, 1998 1849, ibid 1999, 1573.

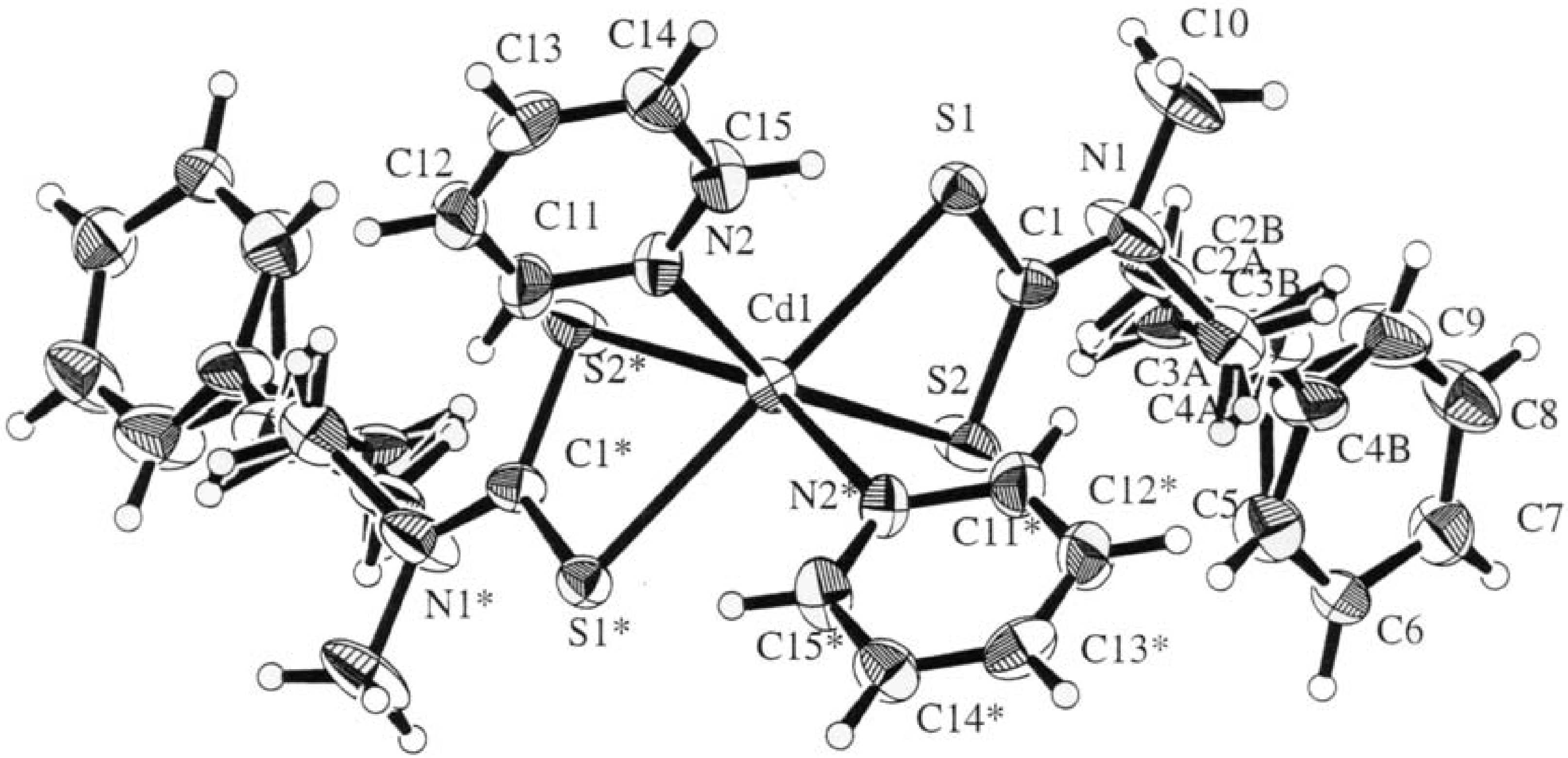


Patent Family
UK patent application No. 9518910.6
PCT application WO 97/10175.
US patent No. 09/043,258 (Granted)
EP patent application No. 96927134.5

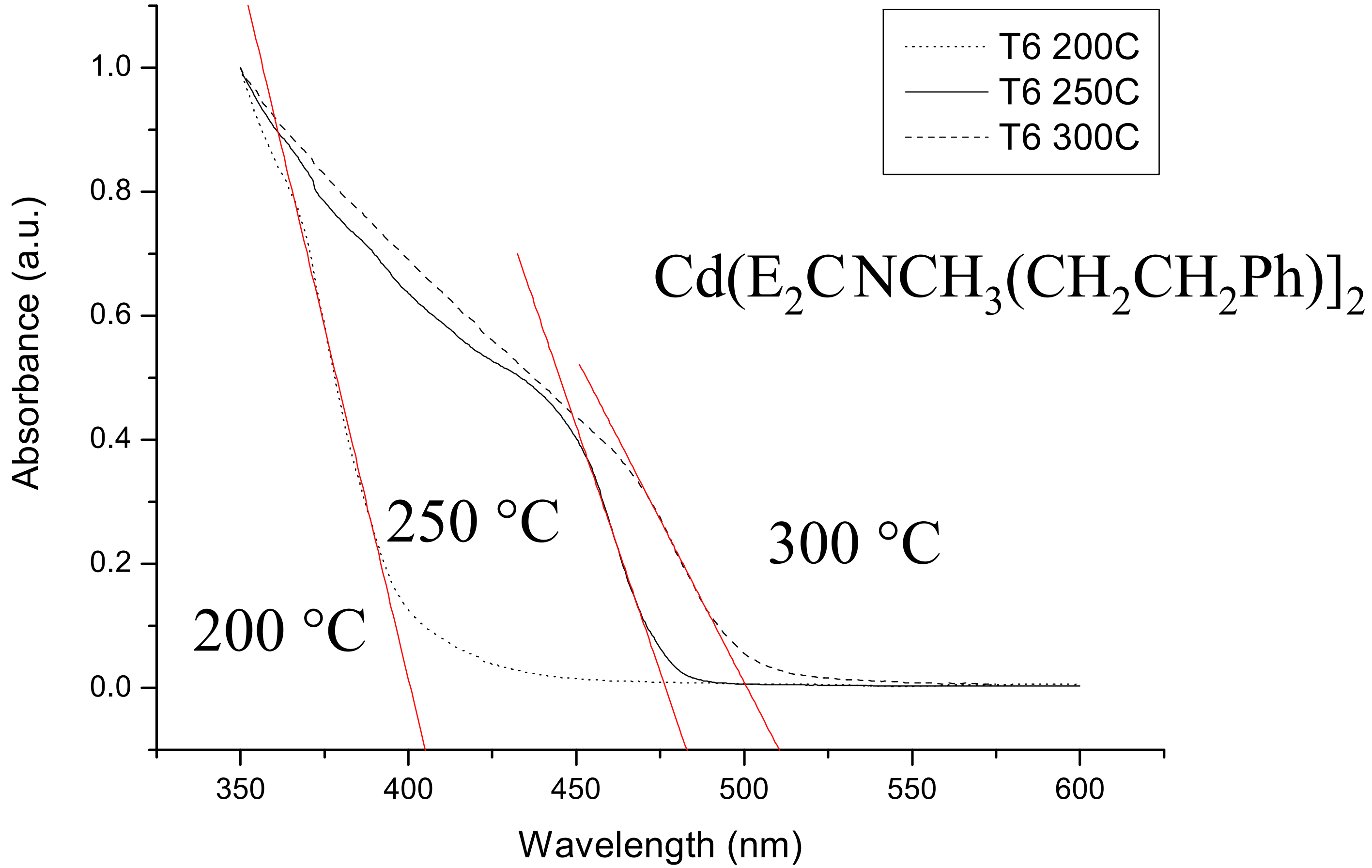
$Me_2Cd + TOPSe \longrightarrow CdSe$

The NanoCo Process

New strategies for the synthesis of nanoparticulates



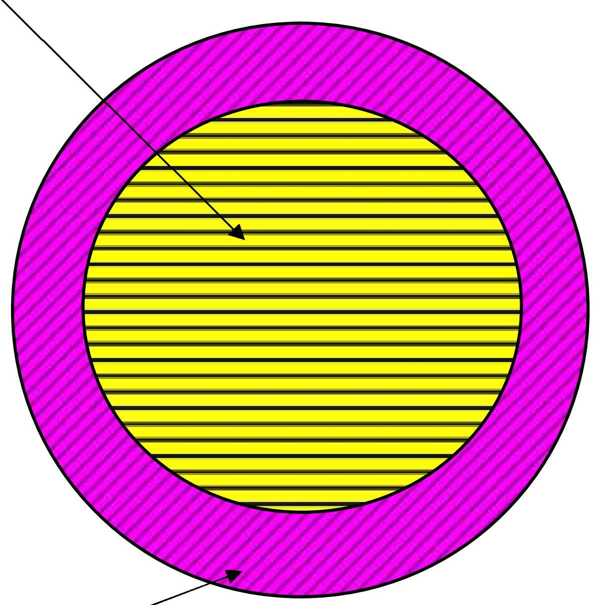
X-Ray single crystal structure of $Cd(E_2CNCH_3(CH_2CH_2Ph)]_2$



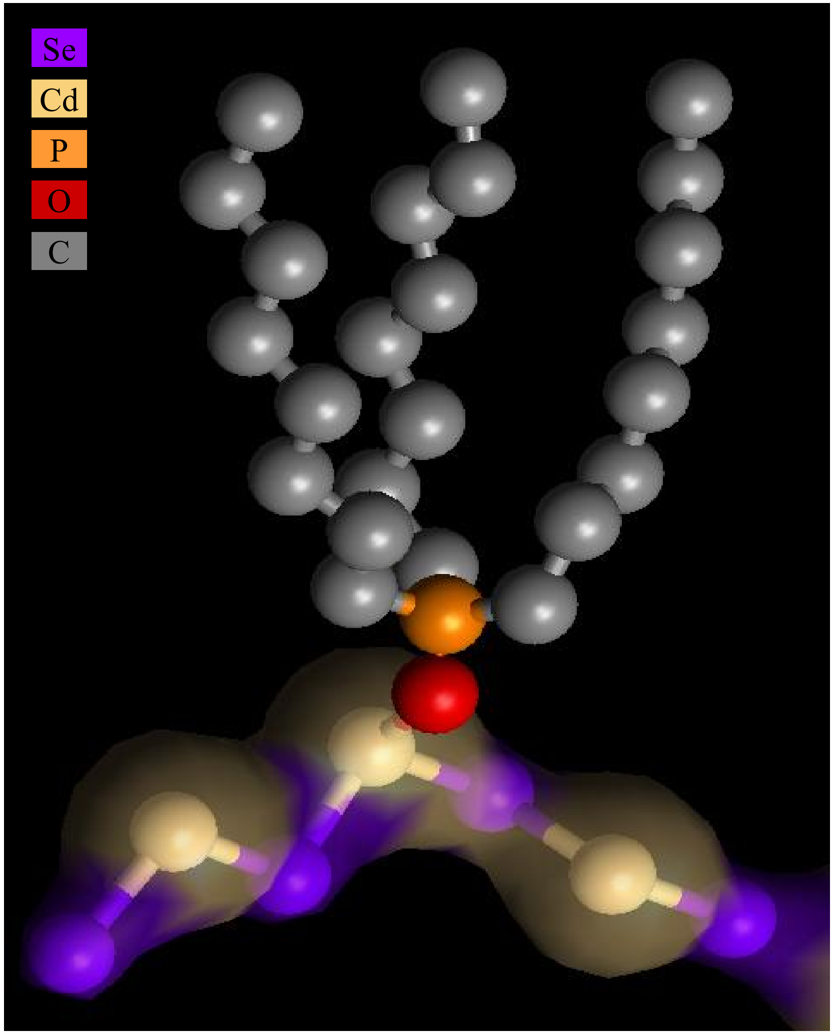
UV-Vis spectra of aliquots T6 (20 min), of runs CdS 200℃, CdS 250℃ and CdS 300℃ fitted to a direct transition.

Quantum Dot Structures I

Crystalline core e.g CdS

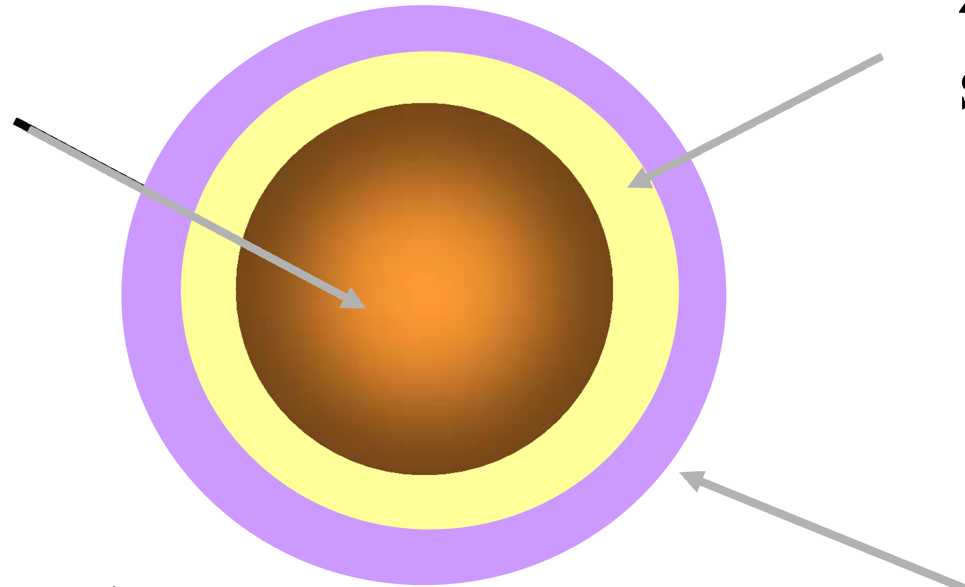


Organic Capping Agent



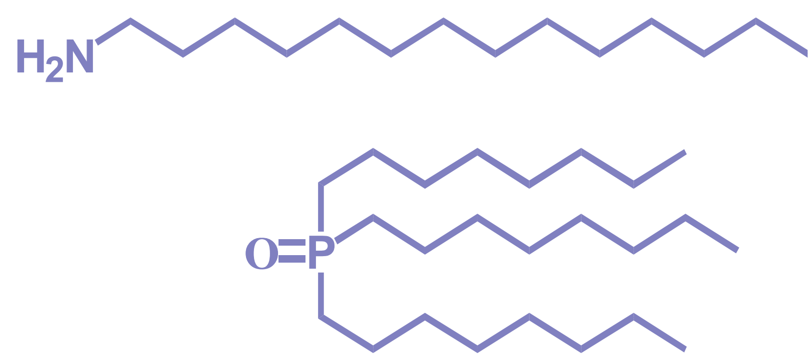
‘Metal Organic Dot’

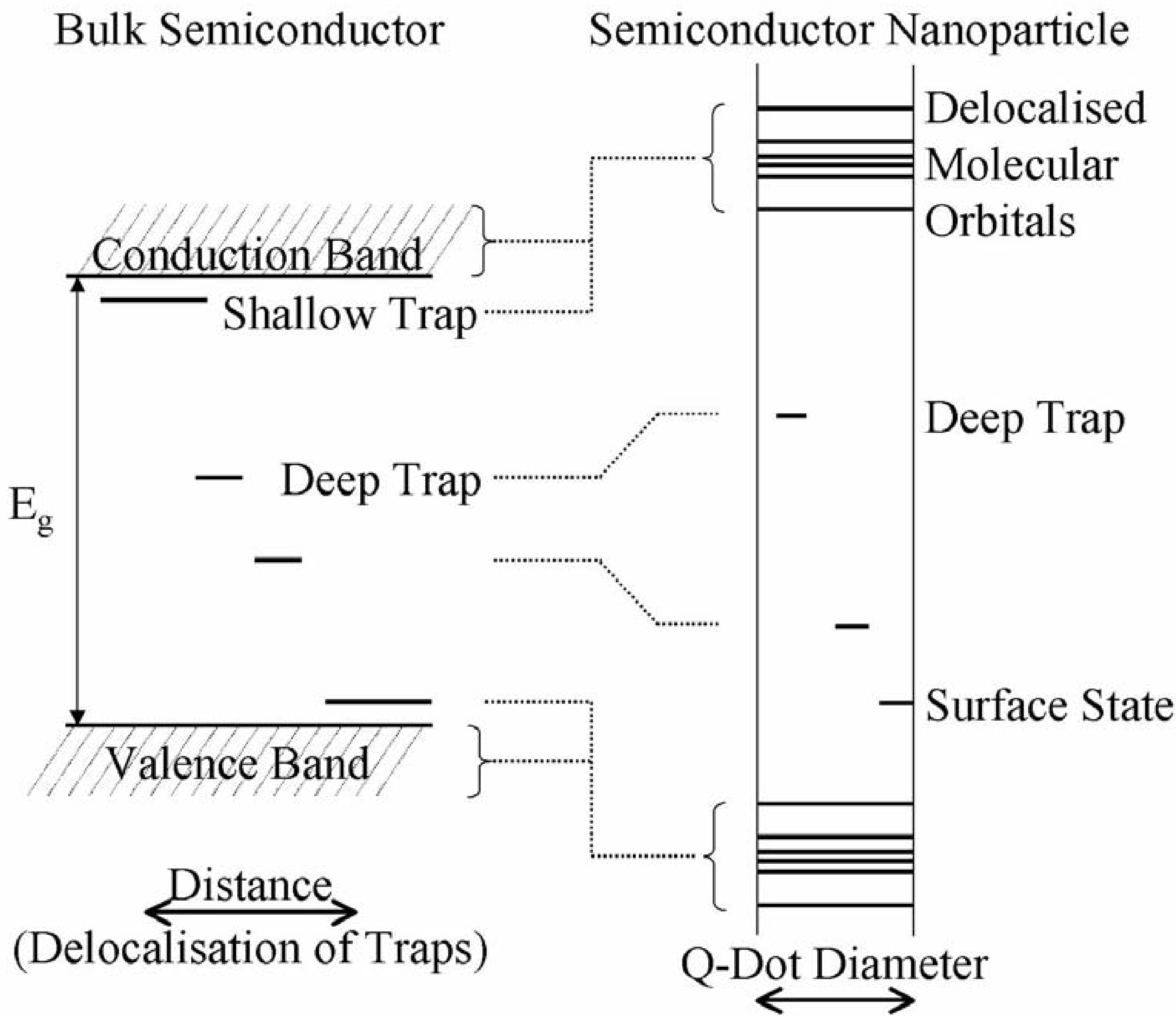
Quantum Dots II

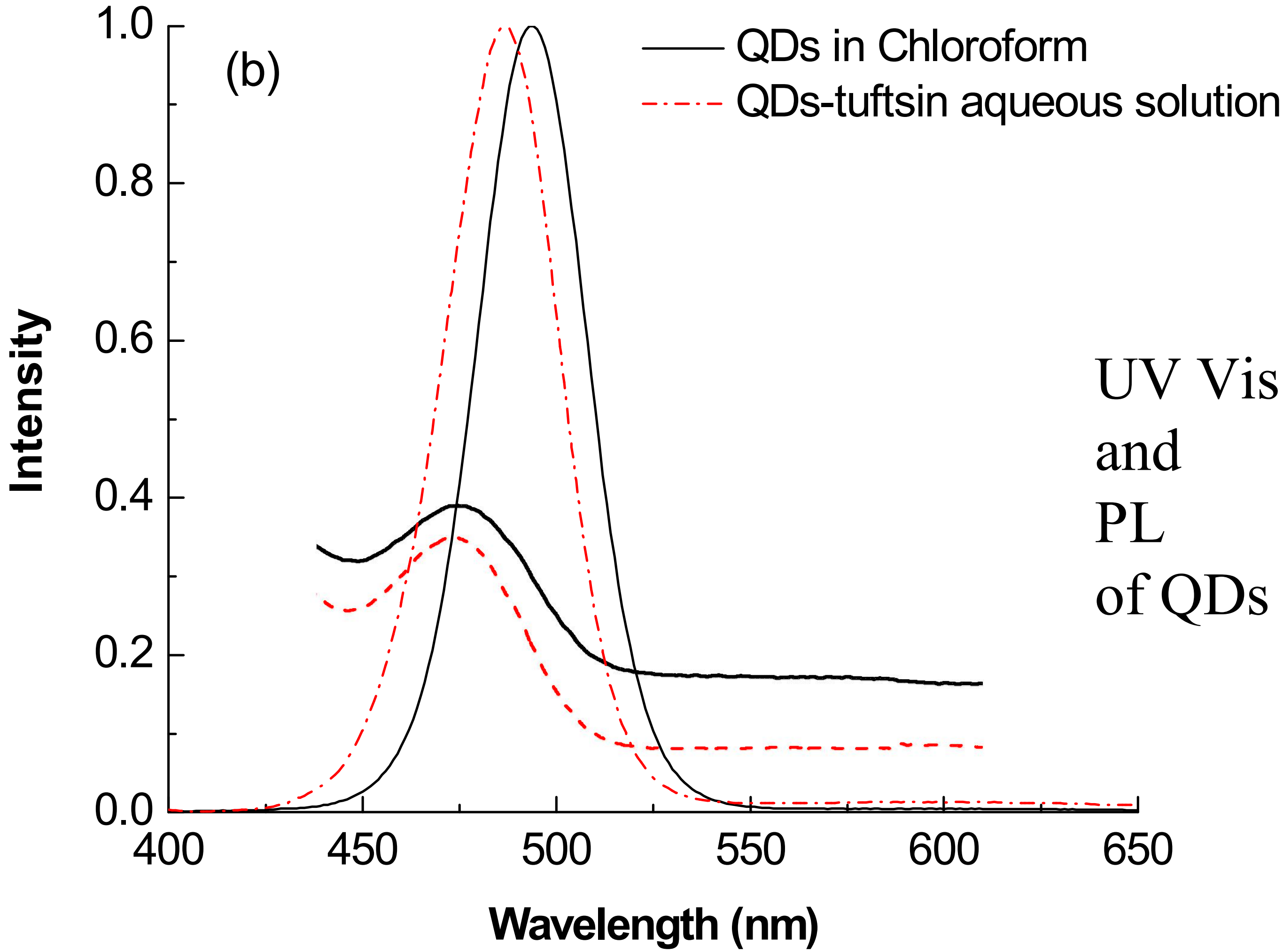


Core Shell Structures

- Broadband excitation
- Narrow bandwidth emission
- Emit light of high intensity
- Available in many colours
- Resistant to quenching
- Photochemically stable




Bulk Semiconductor
Semiconductor Nanoparticle
Delocalised
Molecular
Orbitals
Conduction Band
Shallow Trap
Deep Trap
Deep Trap
E_g
Surface State
Valence Band
Distance
(Delocalisation of Traps)
Q-Dot Diameter



UV Vis
and
PL
of QDs

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JOURNAL OF
Materials
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Controlled synthesis of CdS nanorods and hexagonal nanocrystals

Yunchao Li,† Xiaohong Li,† Chunhe Yang and Yongfang Li*

Key Laboratory of Organic Solids, Center for Molecular Science, Institute of Chemistry, Chinese Academy of Sciences, Beijing, China 100080. E-mail: liyf@iccas.ac.cn

Received 3rd July 2003, Accepted 27th August 2003
First published as an Advance Article on the web 3rd September 2003

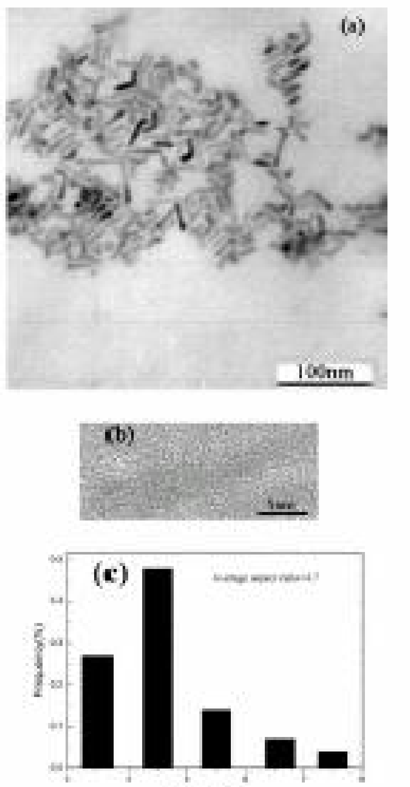


Fig. 7 (a) TEM image of CdS nanorods synthesized at 180 °C for 3 h with a reaction solution of 0.8 g $Cd(C_2H_5OCS_2)_2$ in 4 g HDA. (b) High resolution TEM image of a representative nanorod. (c) Aspect ratio histogram of the nanocrystals.

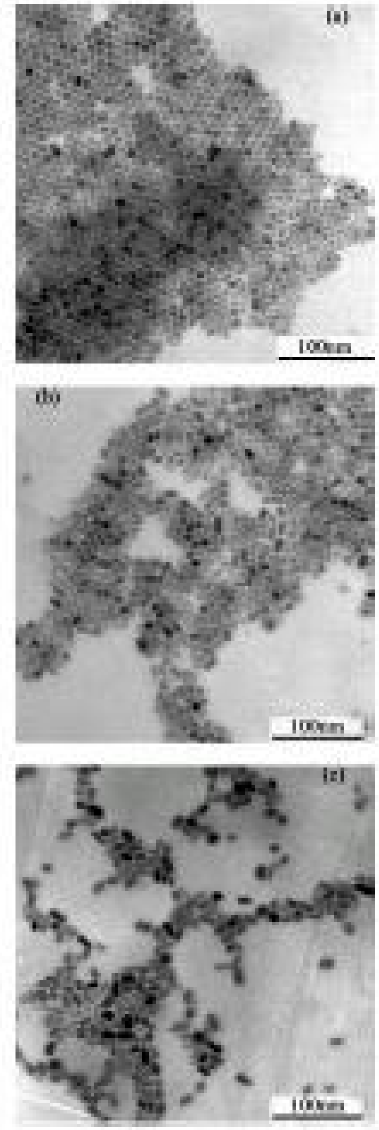
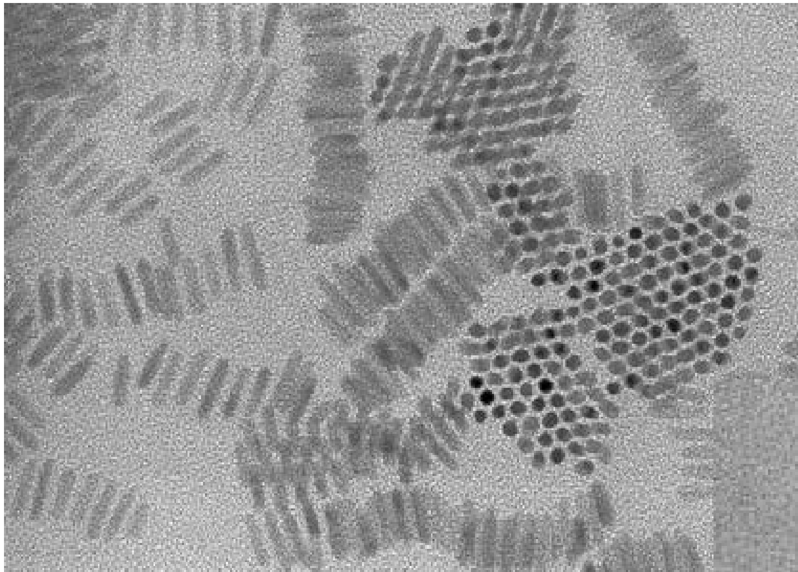
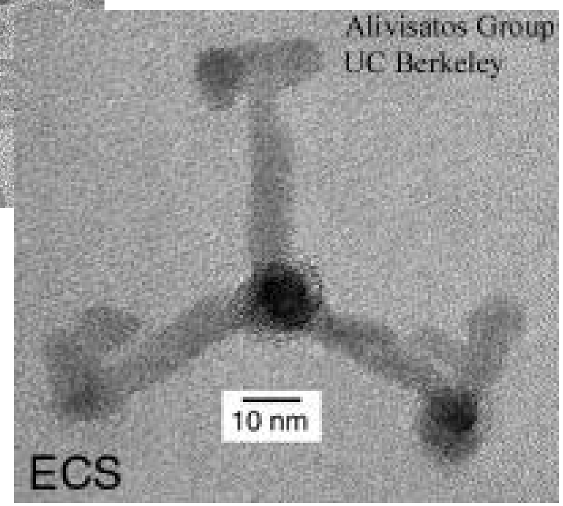
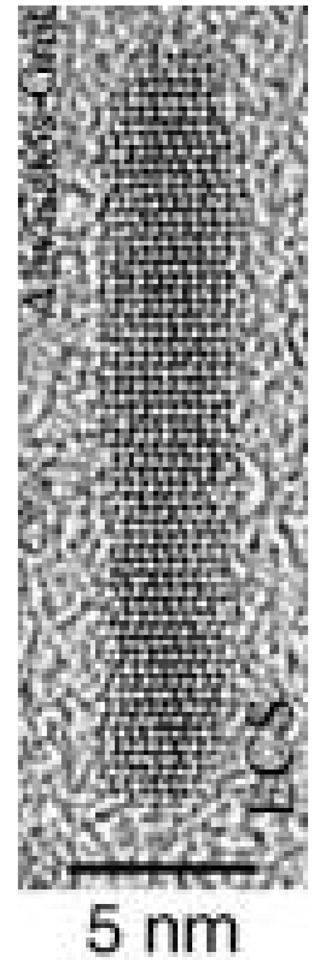
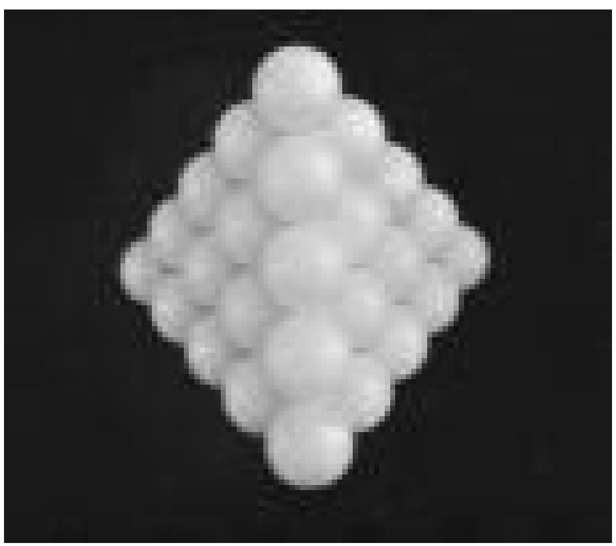


Fig. 4 TEM images of CdS nanocrystals prepared at 260 °C for 3 h, from solutions of (a) 0.1 g, (b) 0.2 g, (c) 0.4 g $Cd(C_2H_5OCS_2)_2$ in 4 g HDA and 2 ml TOP.



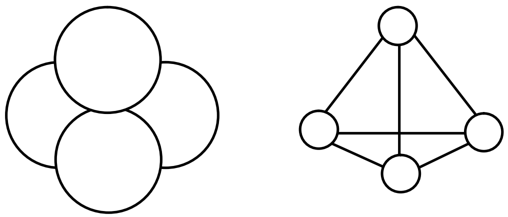

Alivisatos Group
UC Berkeley
10 nm
ECS


5 nm
ECS



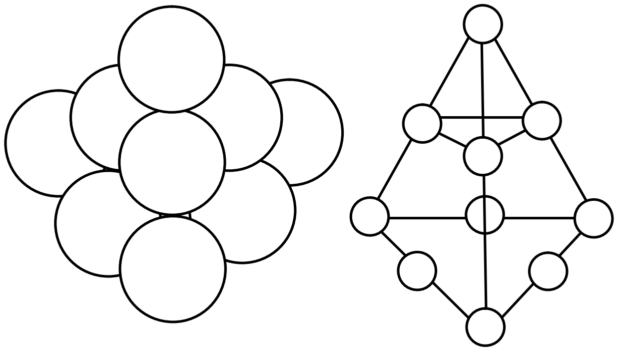
Tetrahedron

N = 2



Total atoms = 4
Surface atoms = 4

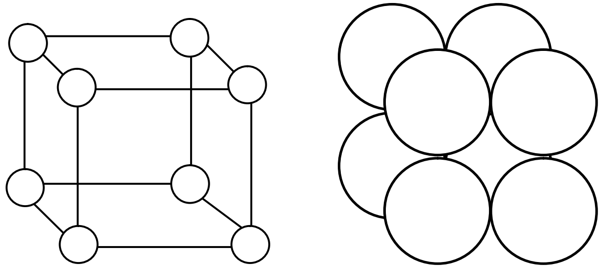
N = 3



Total atoms = 10
Surface atoms = 10

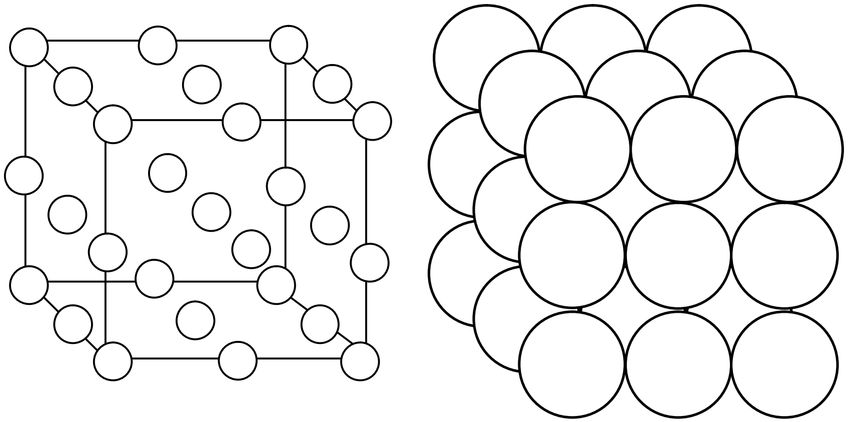
Cube

N = 2



Total atoms = 8
Surface atoms = 8

N = 3

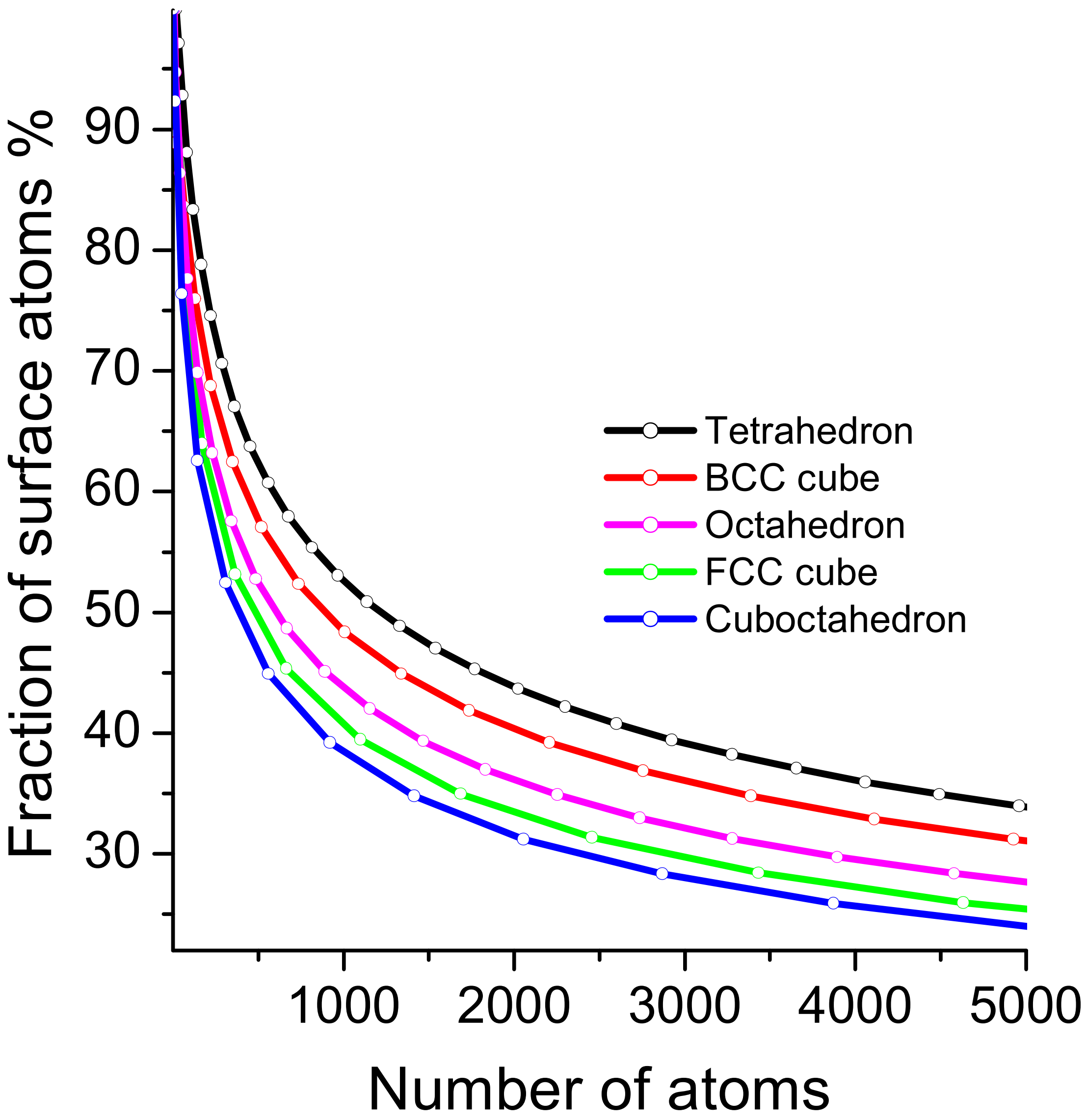


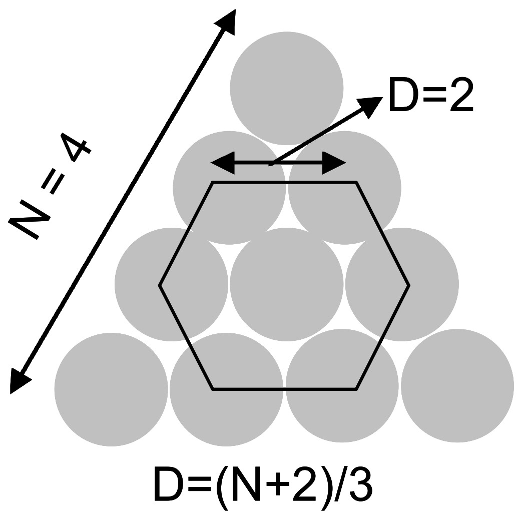
Total atoms = 27
Surface atoms = 26

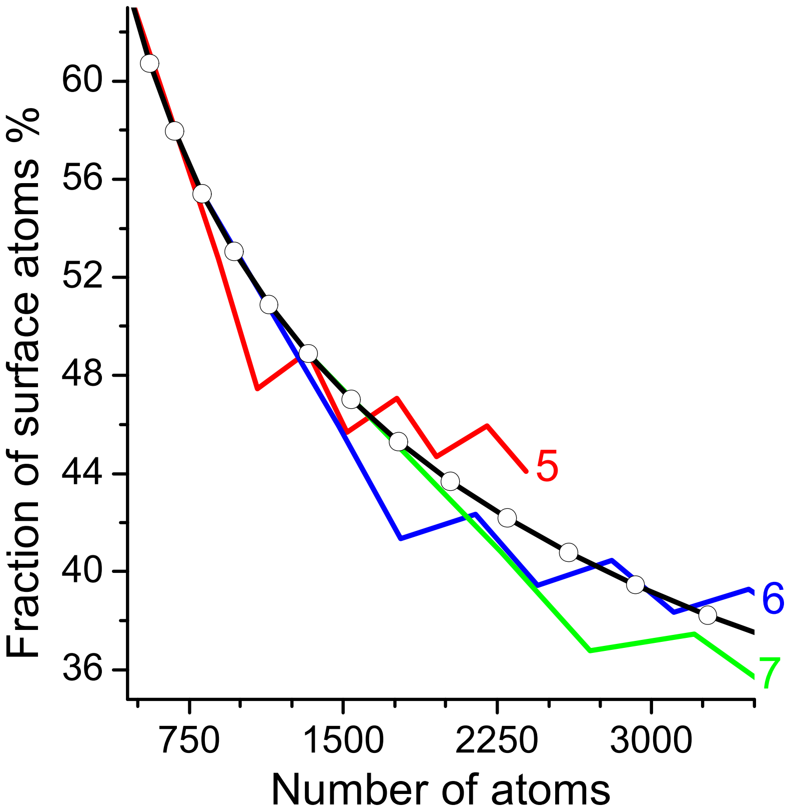
Shape	Total atoms	Surface atoms
Cube Bcc packing	$(N+1)^3+N^3$	$6N^2+2$
Cube Fcc packing	$4N^3+6N^2+3N+1$	$12N^2+2$
Octahedron Fcc packing	$\frac{2N^3}{3}+\frac{N}{3}$	$4N^2-8N+6$
Tetrahedron Fcc packing	$\frac{N^3}{6}+\frac{N^2}{2}+\frac{N}{3}$	$2N^2-4N+4$
Cuboctahedron triangular faces, fcc packing	$\frac{10N^3}{3}-5N^2+\frac{11N}{3}-1$	$10N^2-20N+12$

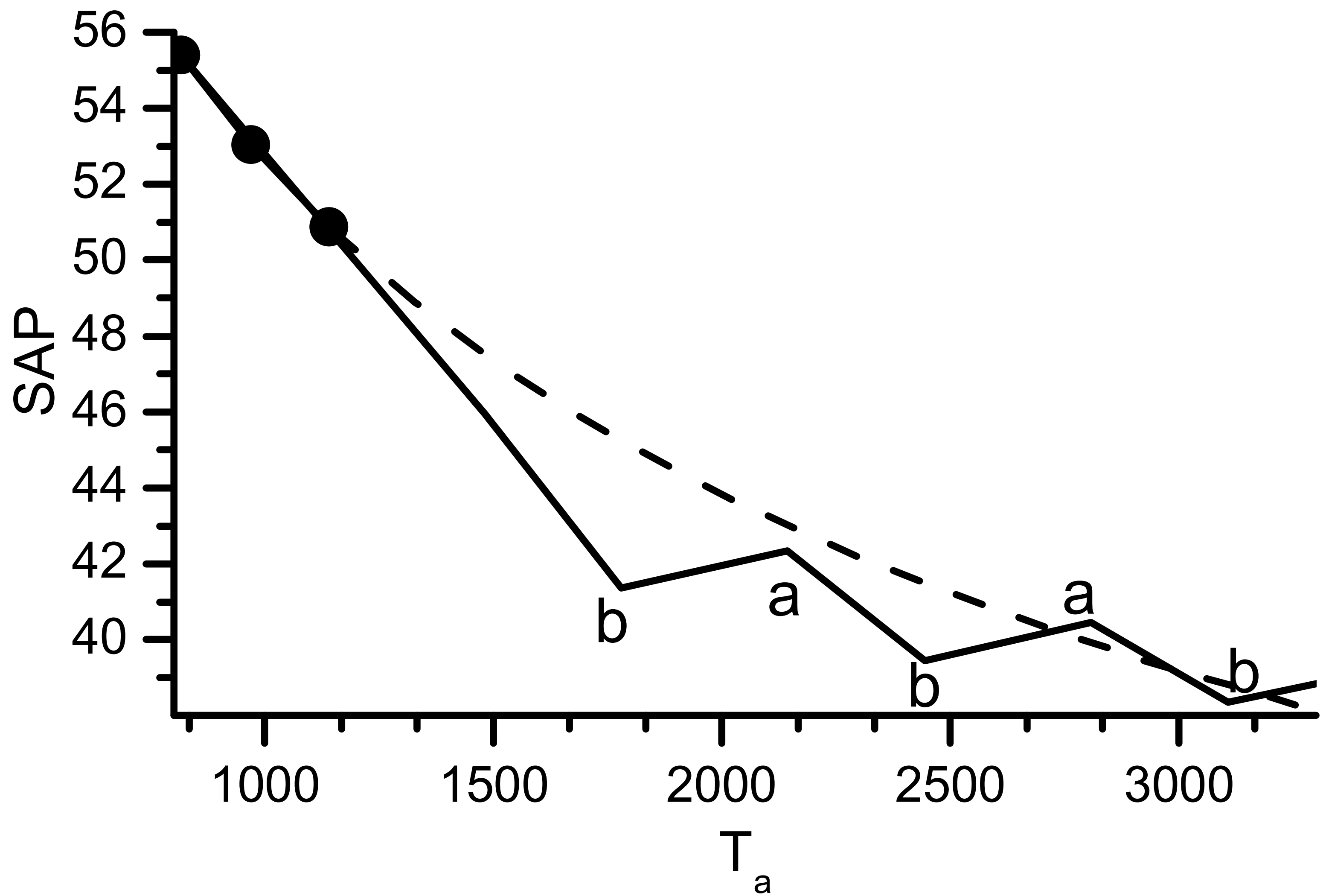
Relationship between the number of shells N and the total number of atoms and surface atoms for different shapes

P. John Thomas and P. O'Brien
J. Amer. Chem. Soc., 128, 2006 5615-5615

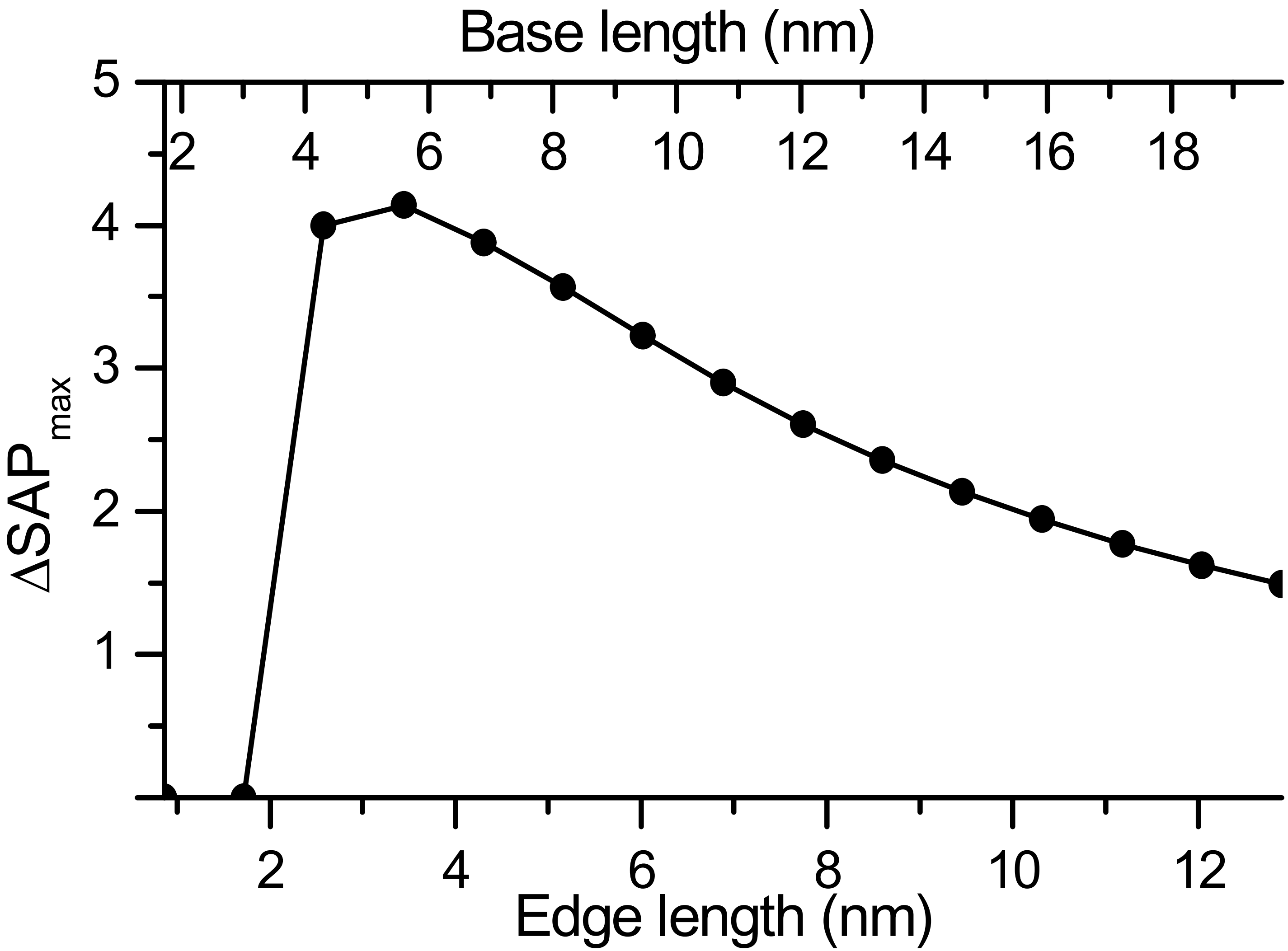

Fraction of surface atoms %
90
80
70
60
50
40
30
1000
2000
3000
4000
5000
Number of atoms
Tetrahedron
BCC cube
Octahedron
FCC cube
Cuboctahedron


N = 4
D=2
D=(N+2)/3

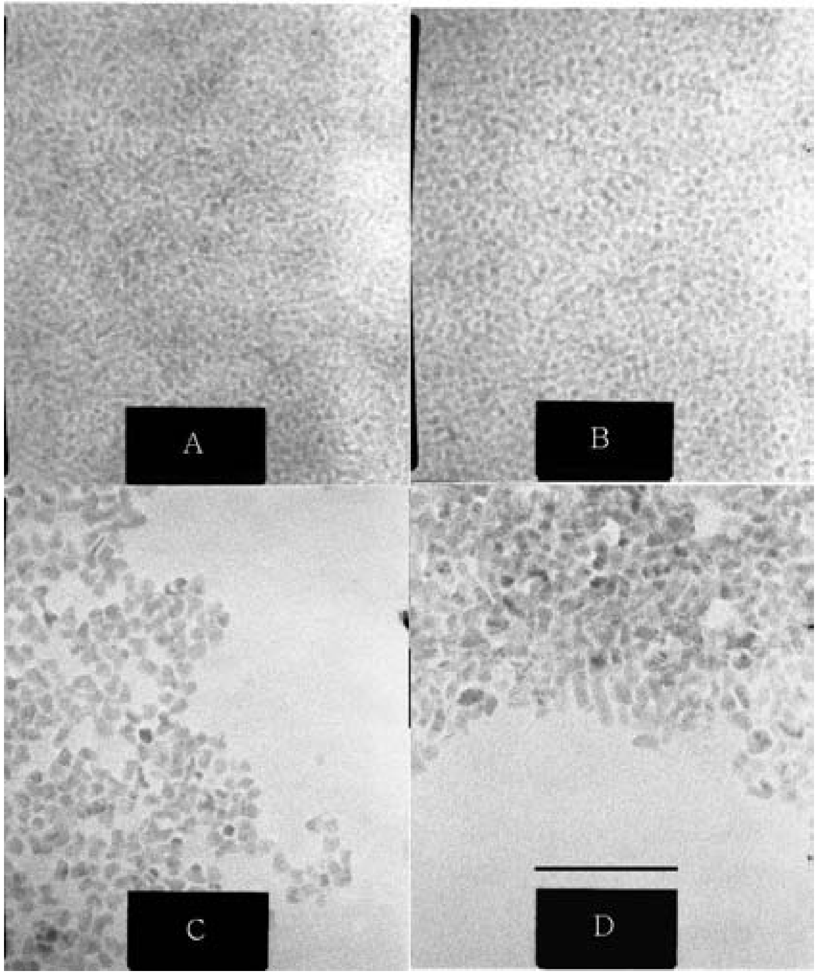

60
56
52
48
44
40
36
Fraction of surface atoms %
750
1500
2250
3000
Number of atoms
5
6
7

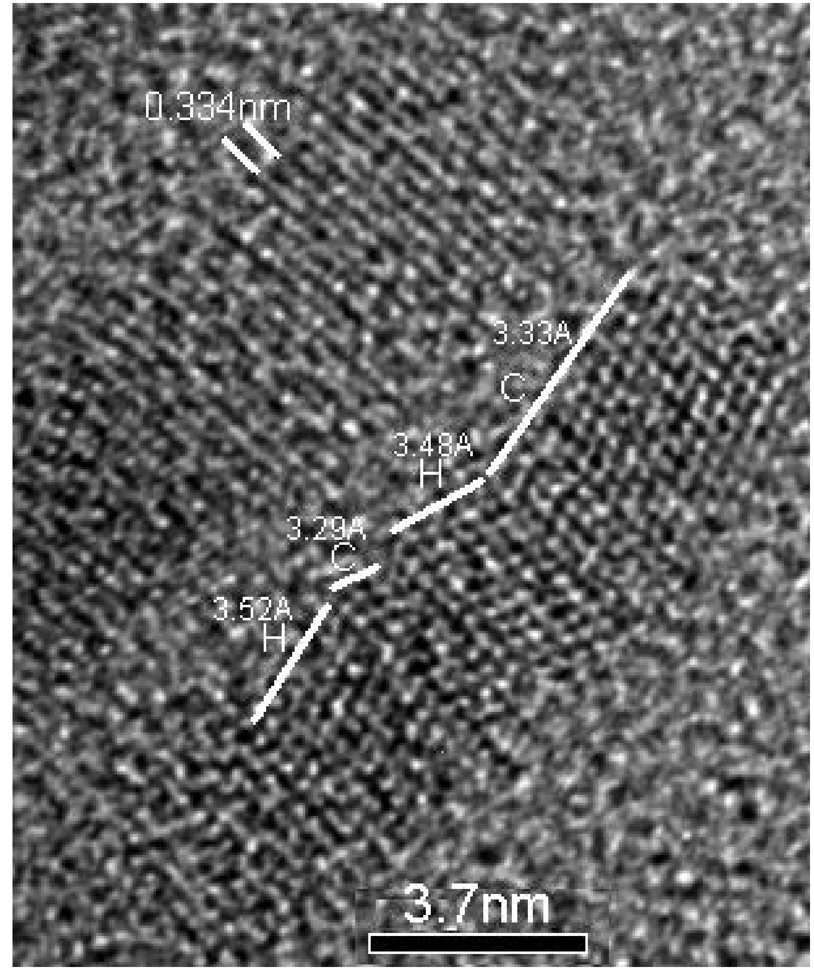


Plot showing the changes in the surface atom percentage (SAP) accompanying the growth of four hexagonal branches. The dotted line represents the SAP profile that the seed would have adopted if branching had not taken place.



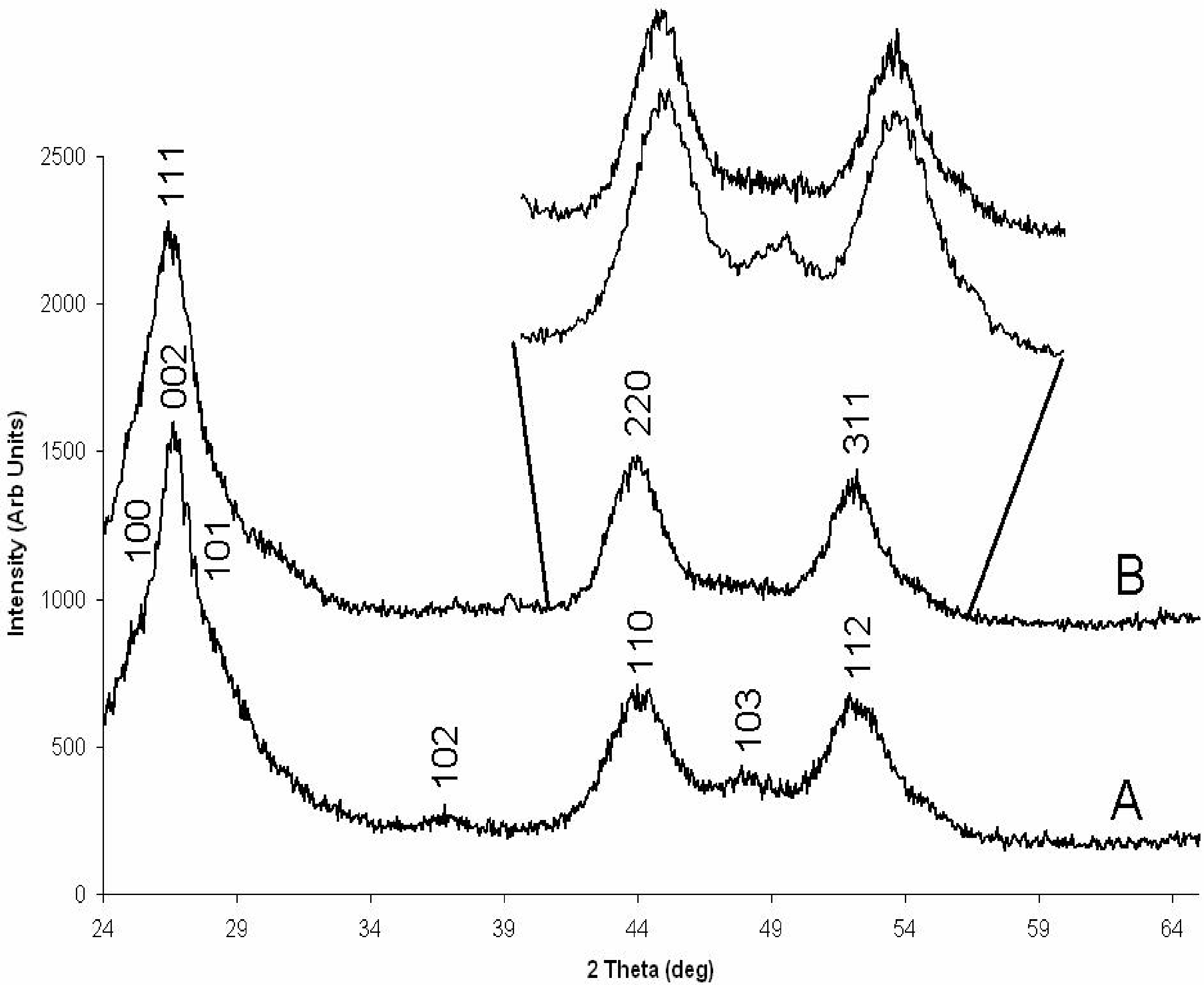
:Plot showing changes in the maximum difference in the surface atom percentage (ΔSAPmax) between the tetrahedron and the corresponding structures with four hexagonal branches grown from a CdSe seed.



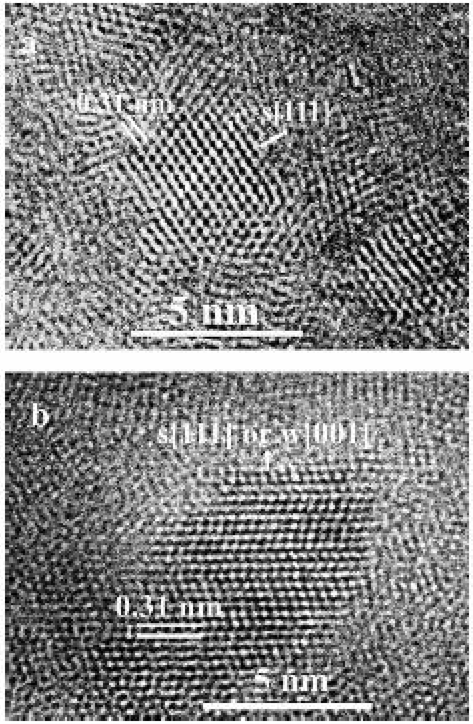


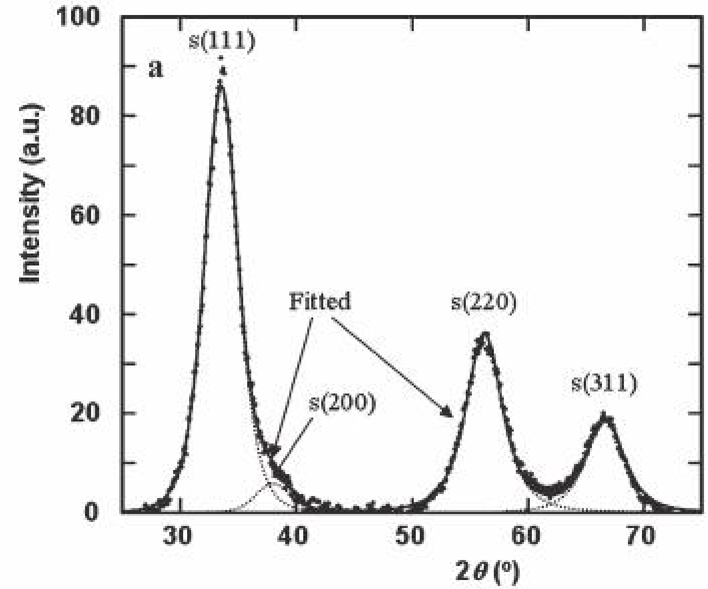
Chem. Comm. 2005 2817-2819

Sample	mmol $CdAc_2$	Final Molarity	λ_{em} (nm)	% rods	Diam** (nm) (std)
A	1.3	0.011	465	<5	3.5 (0.7)
B	2.2	0.018	489	<5	4.0 (1)
C	21.7	0.181	499	~15	6.5 (1)
D	31.6*	0.198	504	72	7.0 (1)



Powder XRD showing hexagonal phase of A and the cubic phase of B. Inset at higher resolution.

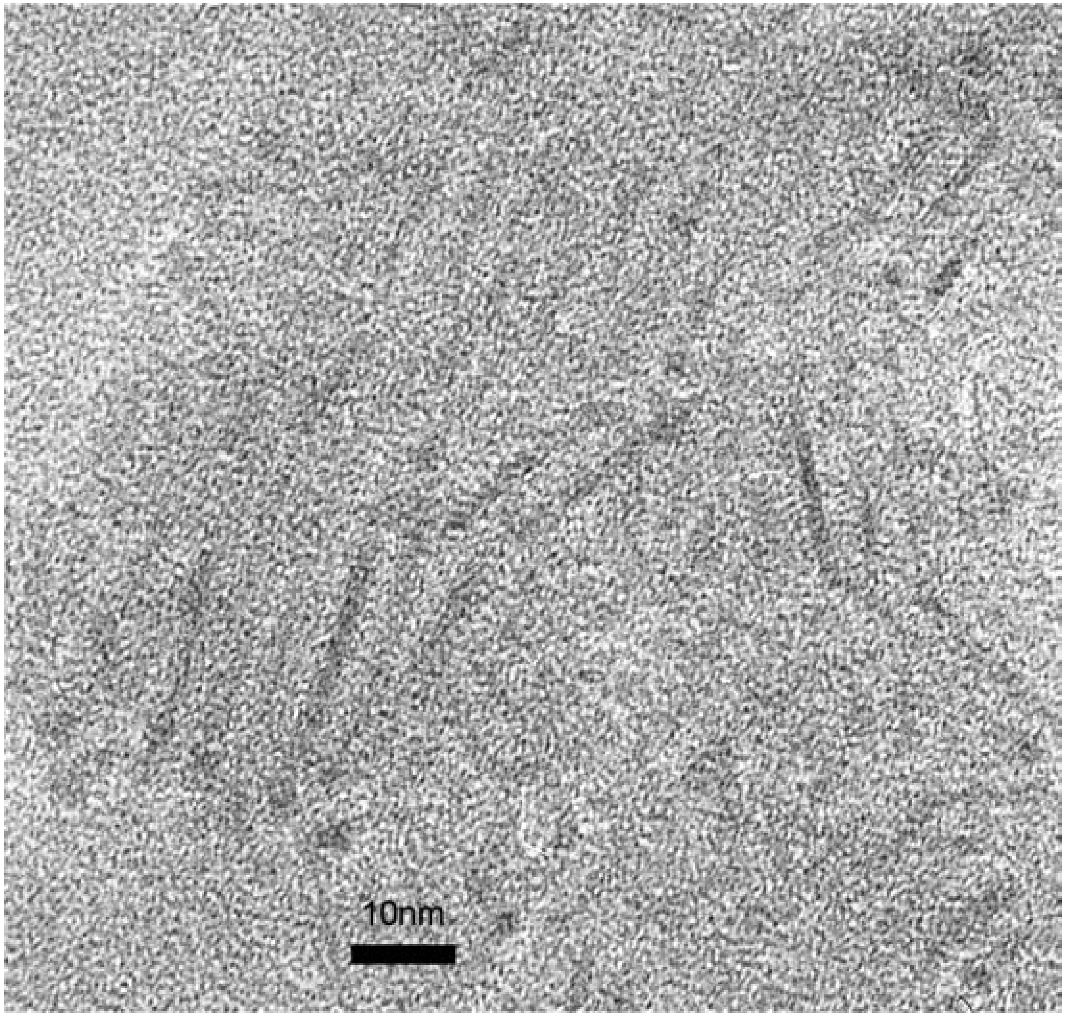


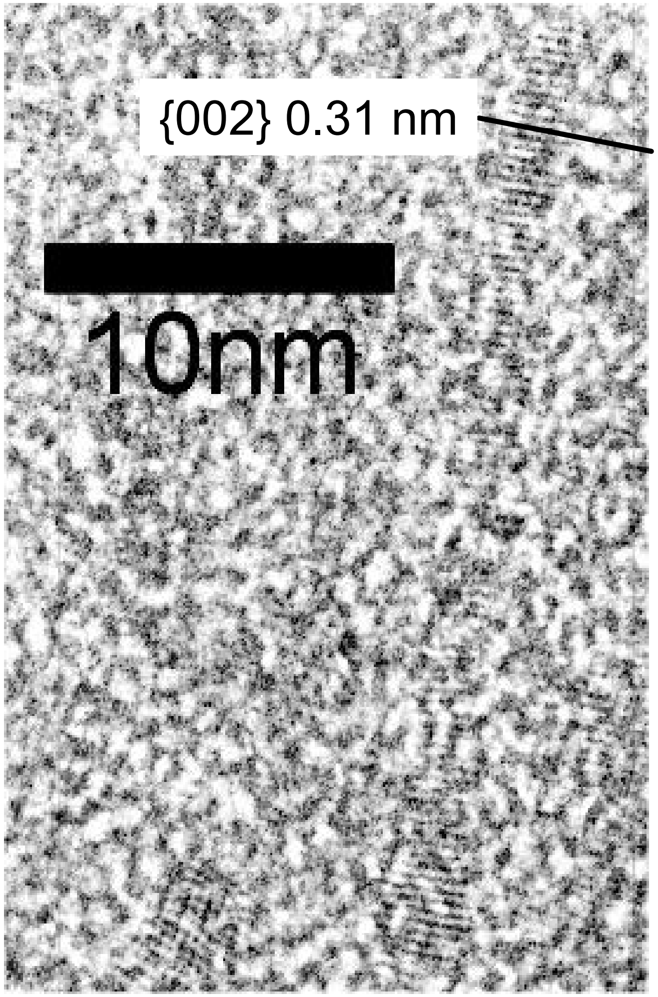


Kinetically controlled formation of a novel nanoparticulate ZnS with mixed cubic and hexagonal stacking†

Hengzhong Zhang,*[a] Bin Chen,[a] Benjamin Gilbert[b] and Jillian F. Banfield[ab]

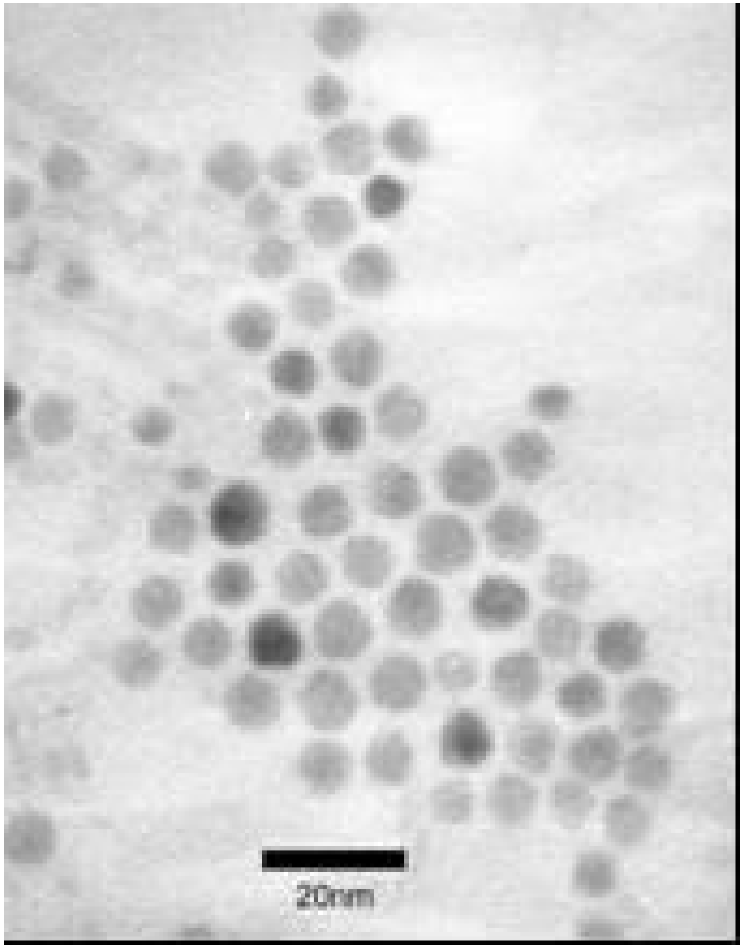
J. Mater. Chem., 2006, 16, 249–254 | 249



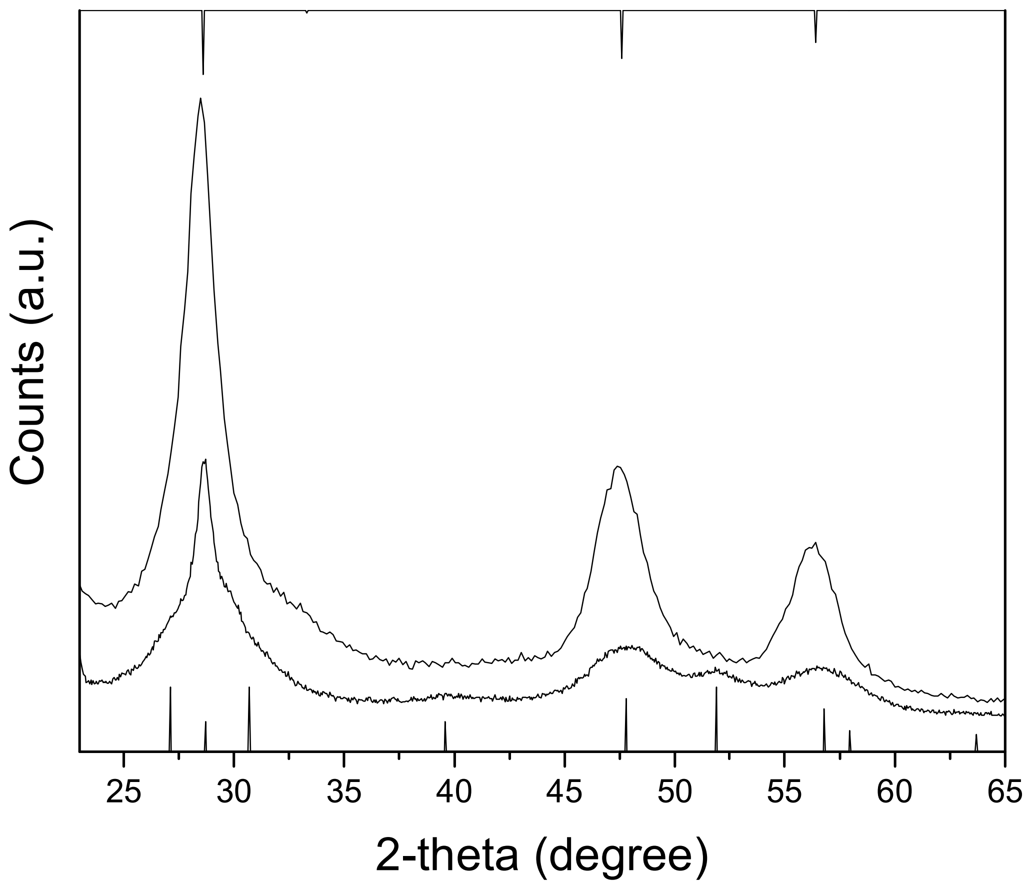


The low temperature (140 ºC) growth of hexagonal ZnS nanorods in a mixture of hexadecylamine and octylamine from sulfur and zinc acetate

J. Experimental Nanoscience 2006, in press.



ZnS as before but at 180 º C



XRPD of ZnS (a) rods grown at 140°C and (b)dots grown at 180°C. Also shown are the bulk indices for hexagonal (below) and cubic (top).

MANCHESTER 1824

The University of Manchester

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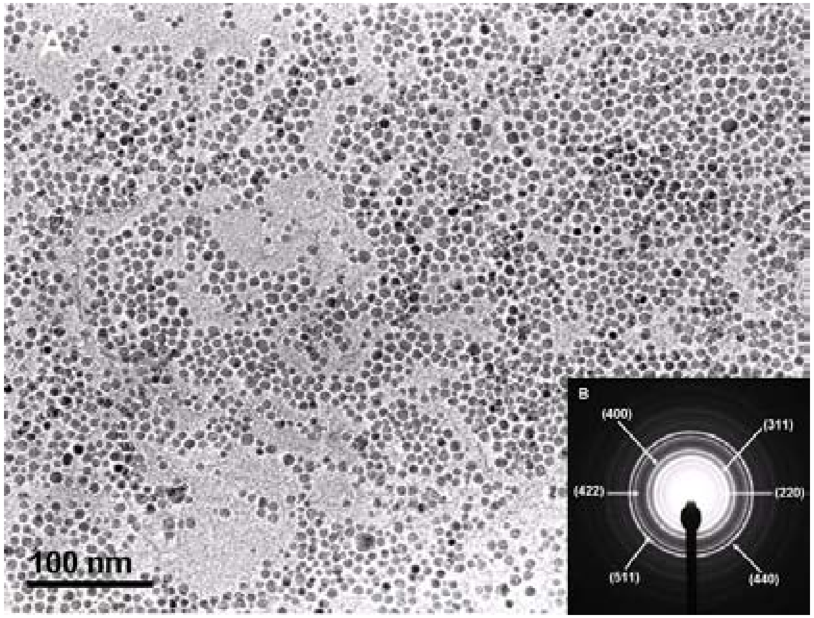
- Closing remarks

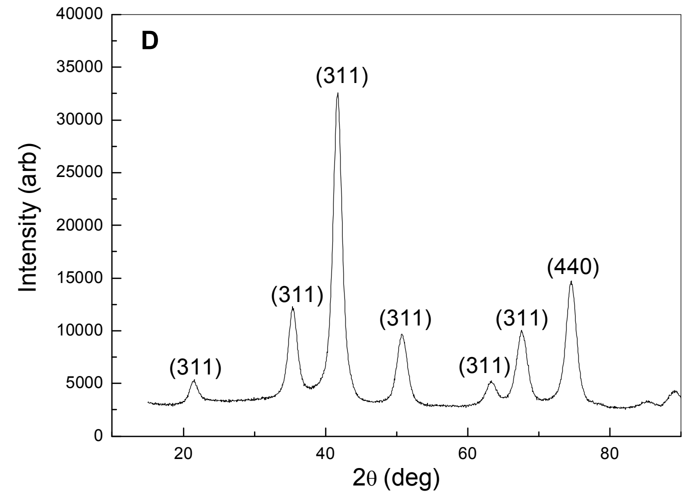
Some Oxides…………..

Precursor	Solvent	Reaction T_m	Time (hour)	Product and Size
$Fe(acac)_3$	HDA	250 °C	2	Fe_3O_4 10.5 nm
$Mn(acac)_2$	HDA	270 °C	1	MnO 17.5 nm
$Co(acac)_2$	HDA	240 °C	3.5	CoO 20.0 nm
$Ni(acac)_2$	HDA+TOPO (2:1 w/w)	220 °C	2	NiO 14.0 nm
$Cr(acac)_3$	HDA	340 °C	3	No Reaction

Generic routes to metal oxides

J. Mater Chem in press 2006

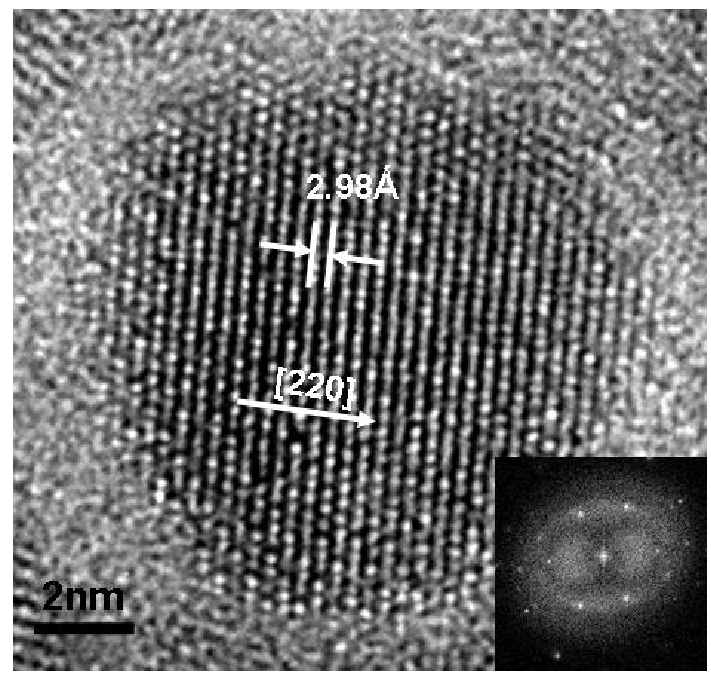


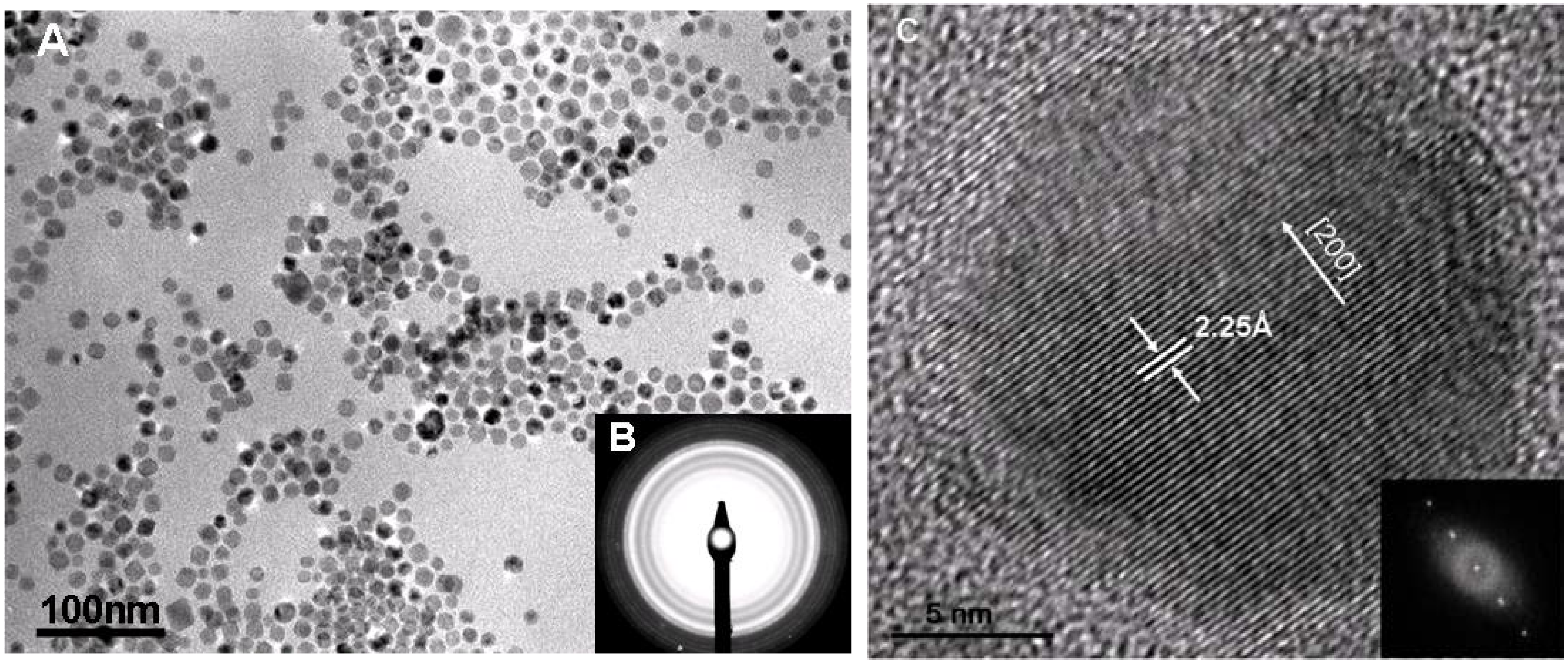


(A) TEM image, (B) Selected area electron diffraction (SAED) pattern acquired from the corresponding Fe_3O_4 nanoparticles,

(C) HRTEM image of a 10 nm diameter of Fe_3O_4 nanoparticle, (insert) FFT of the HRTEM,

(D) XRD pattern of Fe_3O_4





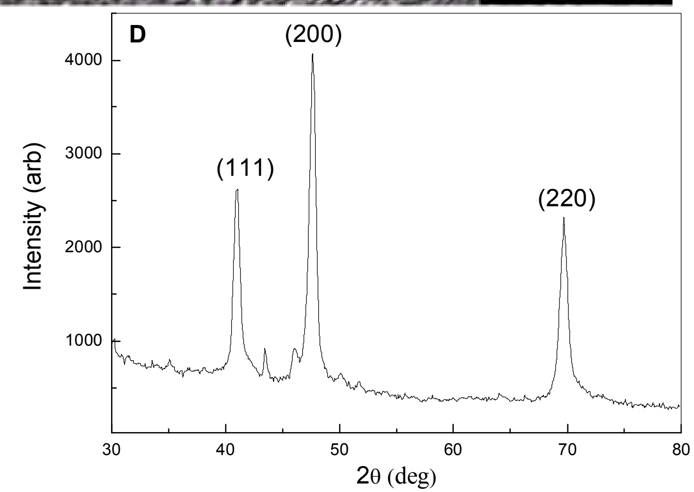
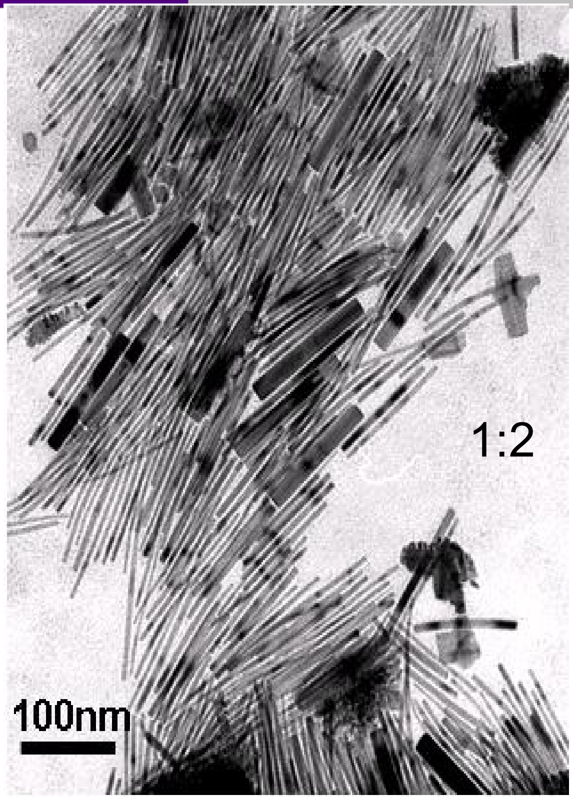


Fig. 3 (A) TEM image, (B) SAED pattern acquired from the corresponding MnO nanoparticles, (C)HRTEM image of a 18 nm diameter of MnO nanoparticle, (insert) FFT of the HRTEM, (D) XRD pattern of MnO

Some Cobalt Phosphide………..



TEM images of CoP nanowires prepared with different weight ratios of HDA to TOPO:

However, the reaction of $[Co(acac)_2]$with TOPO as the only solvent did not give any wires of CoP even at 360 ^{o}C over three hours. Similar experiment in HDA alone gave only CoO nanoparticles.

J. Amer. Chem. Soc., 2005, 127, 16020-16021

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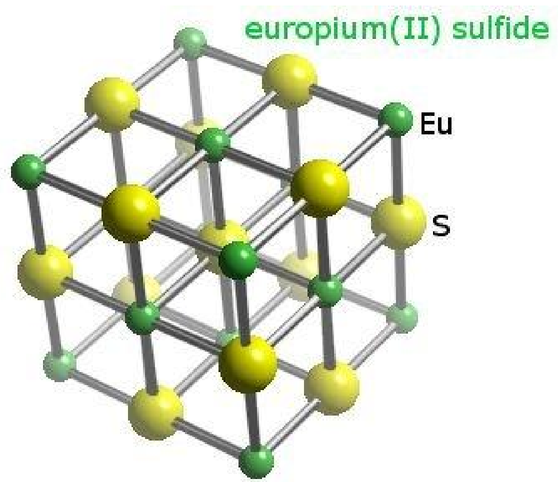
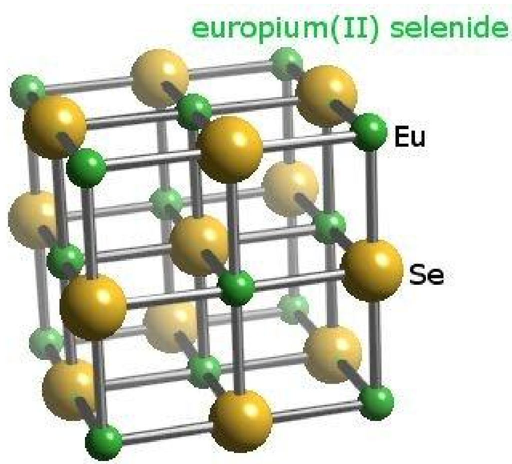
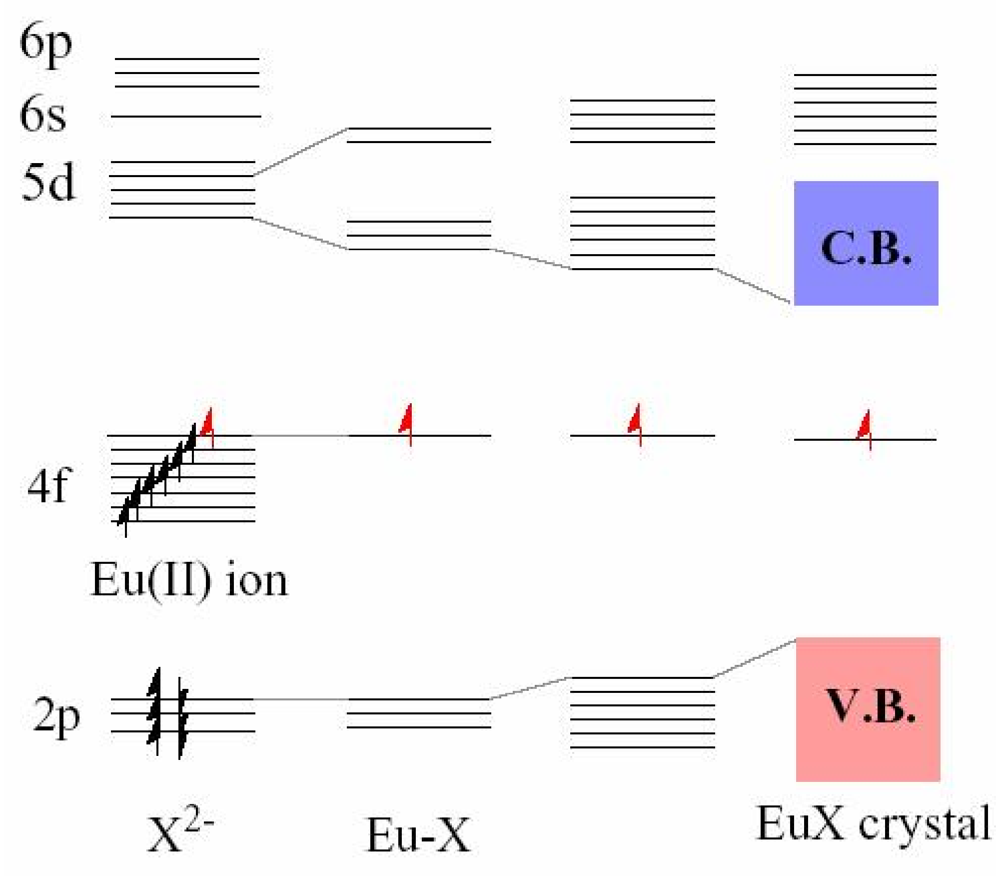
EuS and EuSe…………..

Eu(II) chalcogenide nanocrystals

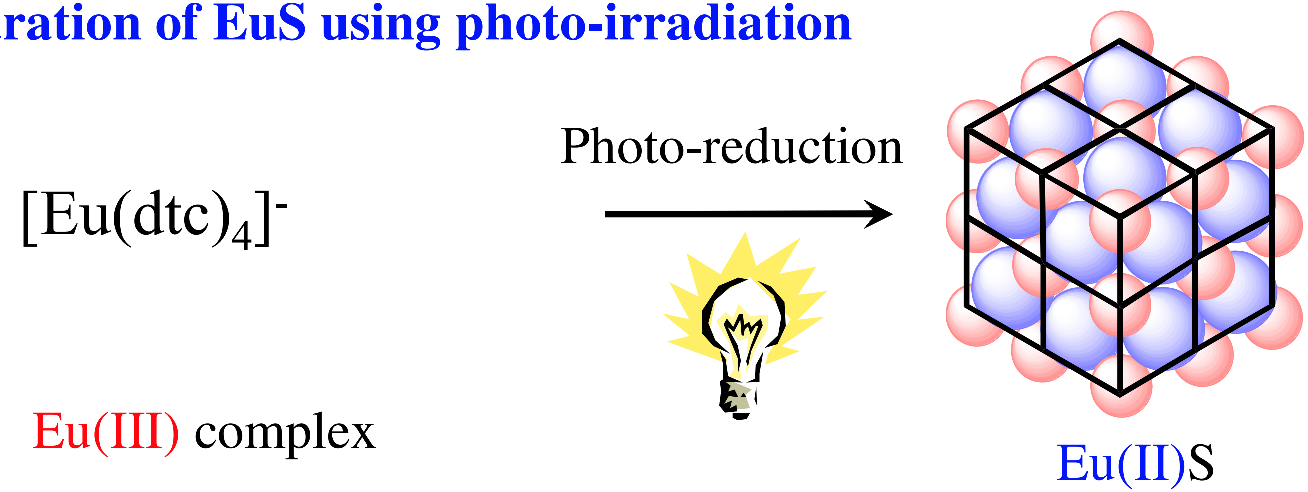




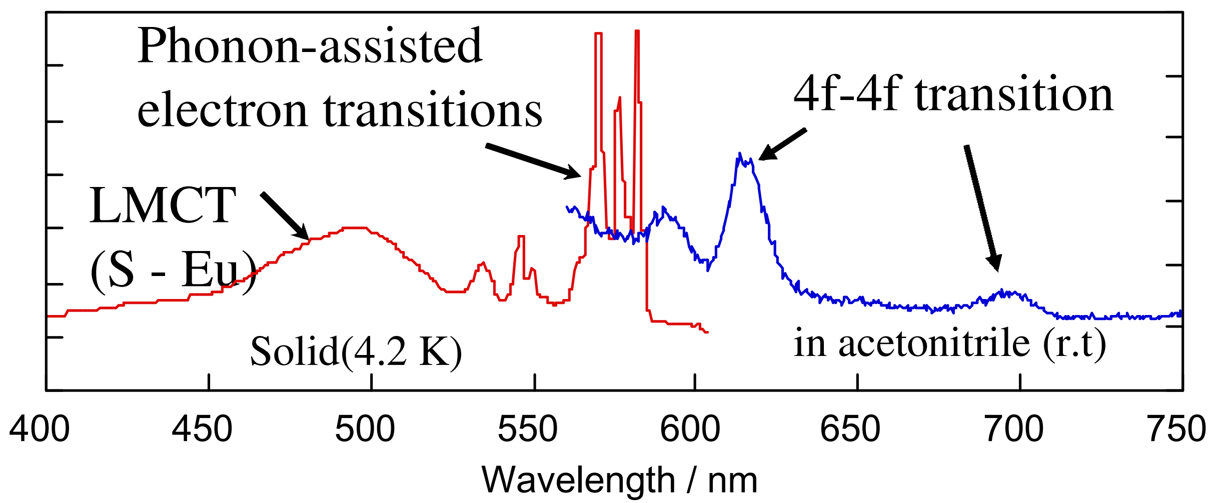


NaCl type structures

Preparation of EuS using photo-irradiation

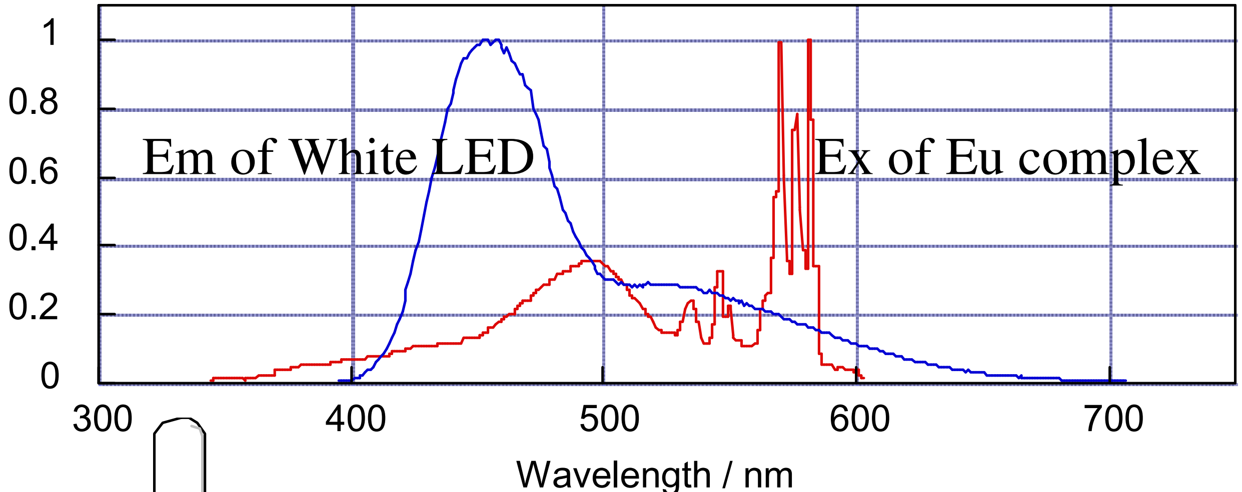


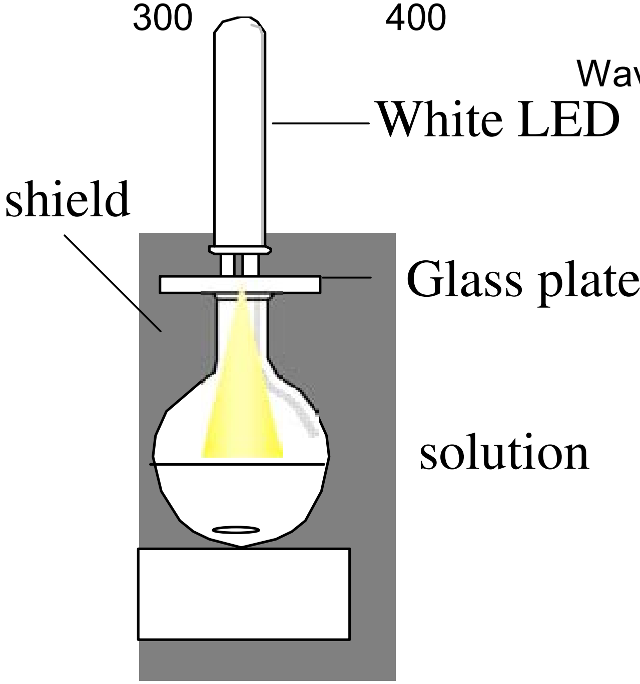
Energy levels of EuS-complex



Excitation spectrum from ‘T. Yamase et al, *Chem. Lett.*, 907 (1997)

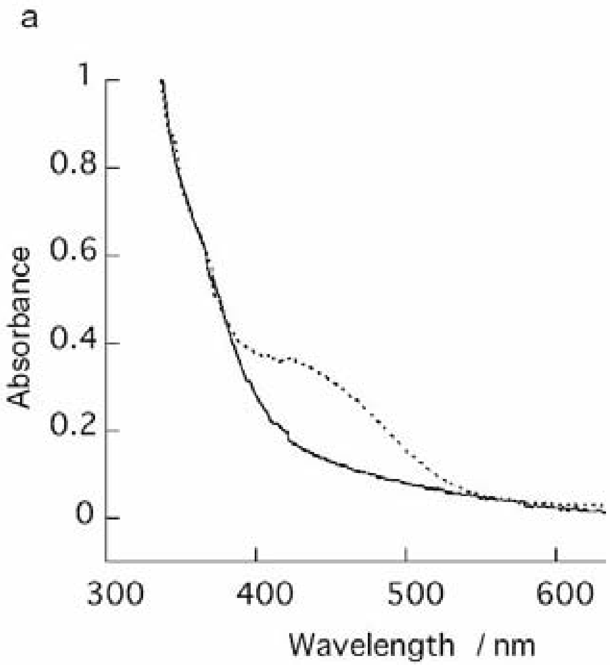
White LED for excitation light source

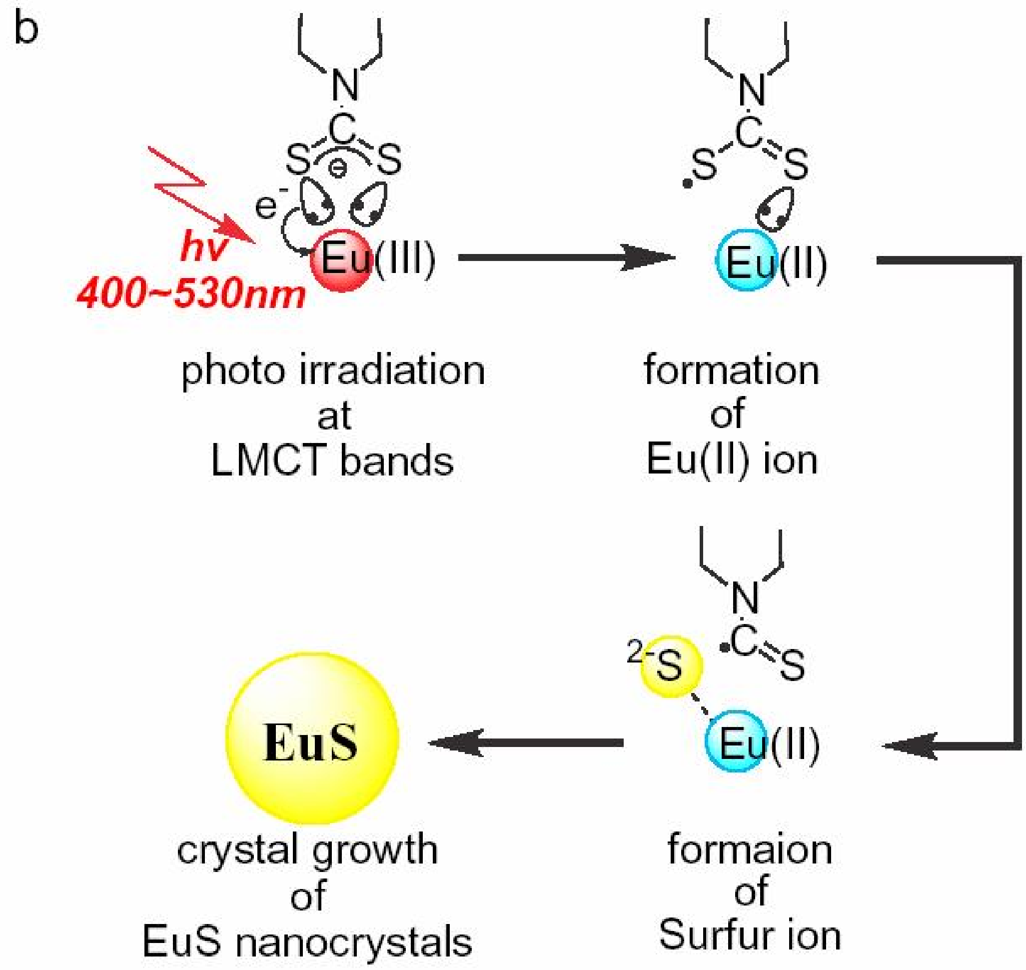




$Na[Eu(S_2CEt_2)_4]\cdot 5H_2O$
in acetonitrile (1 mM)
Absorbance ~ 0.4 / cm (440 nm)
for 3 days

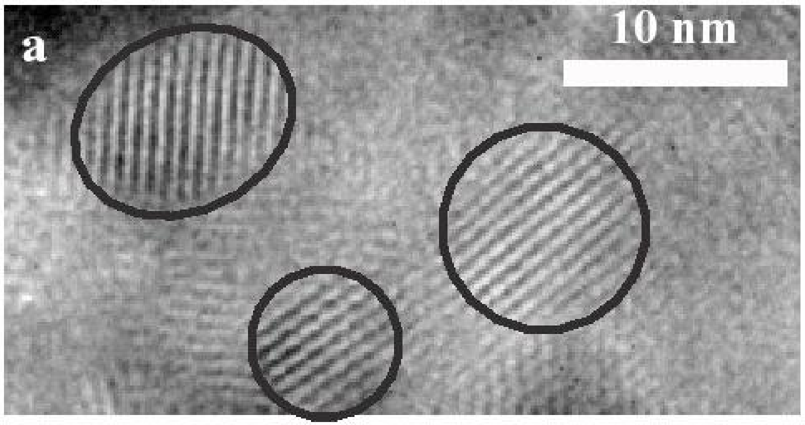
EuS nanoparticles from single-source precursor

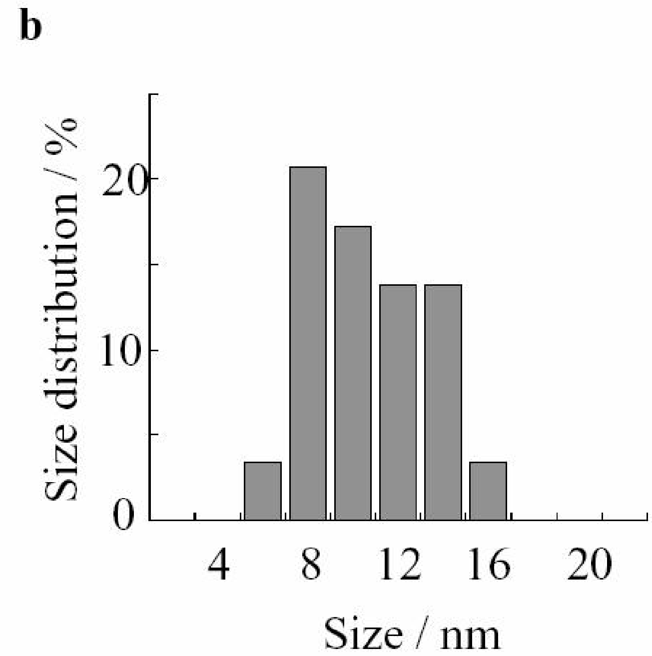


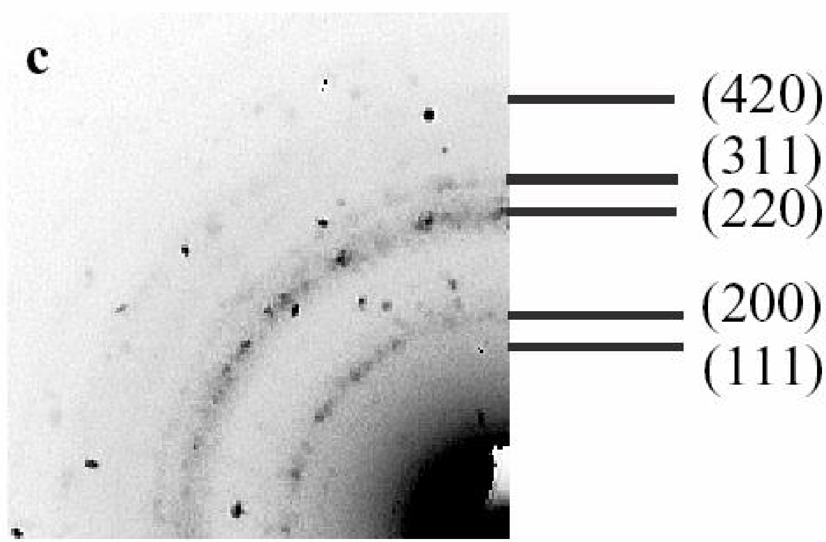


Y. Hasegawa, M. Afzaal, P. O'Brien, Y. Wada, S. Yanagida, Chem. Commm., 2005 242-244

TEM observations







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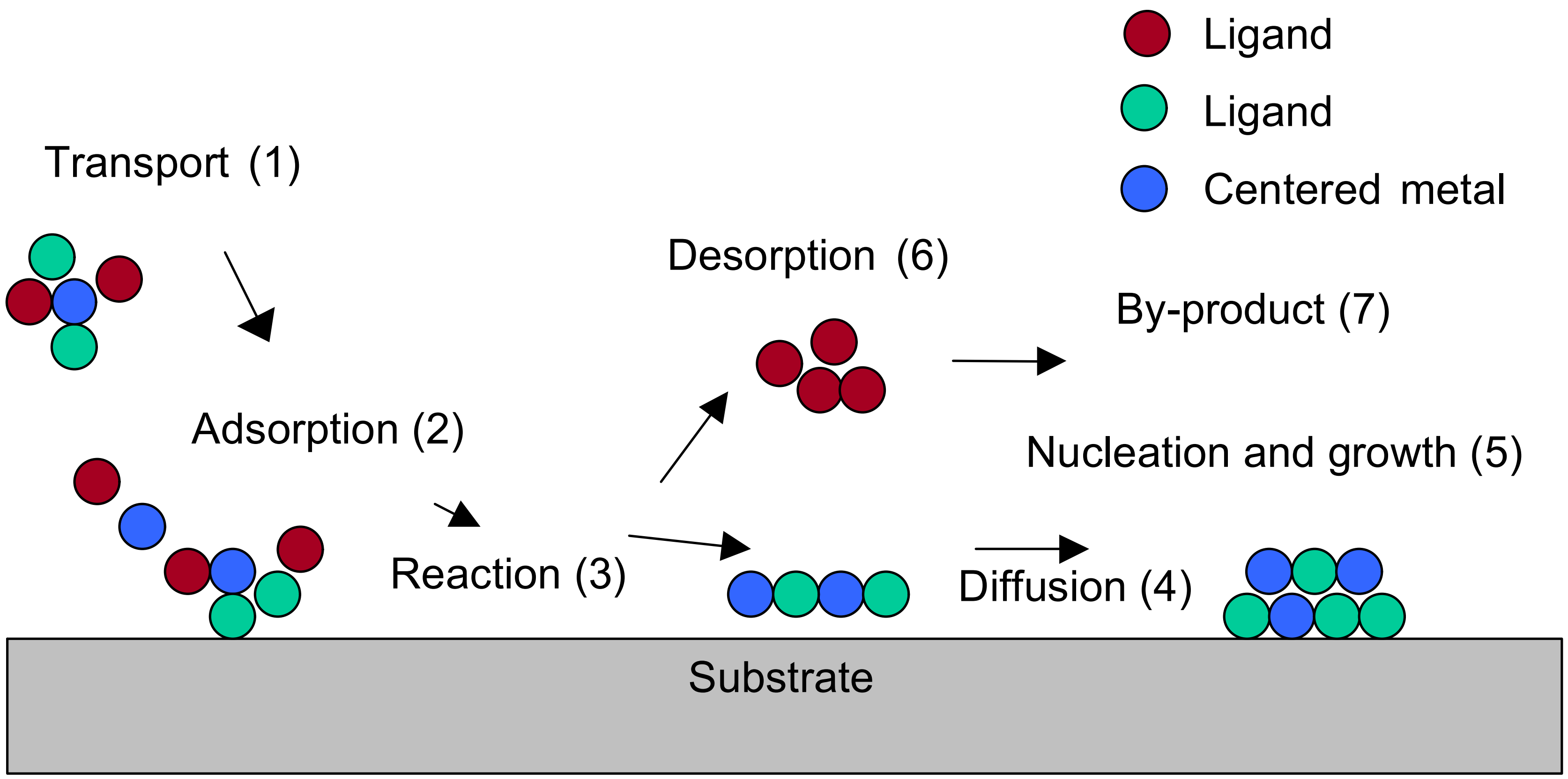
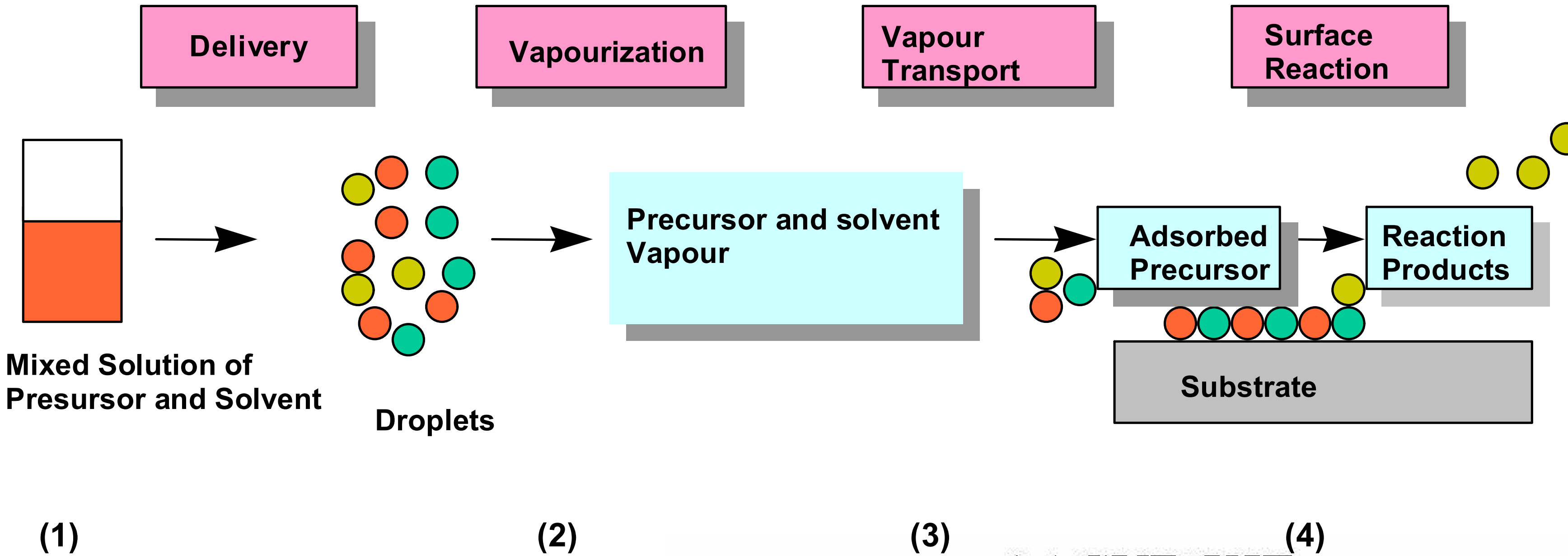
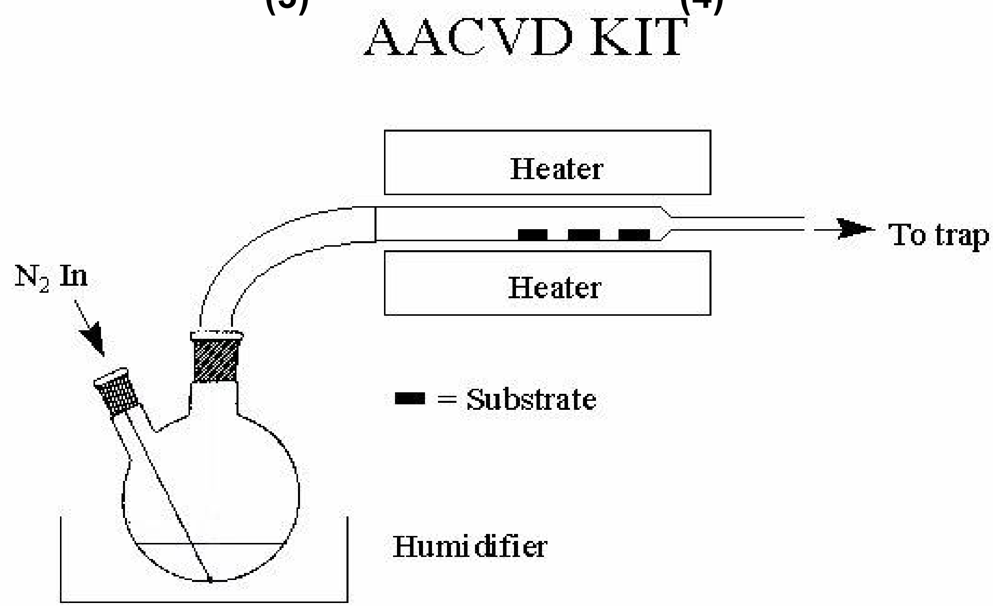
Sulfides by CVD………..

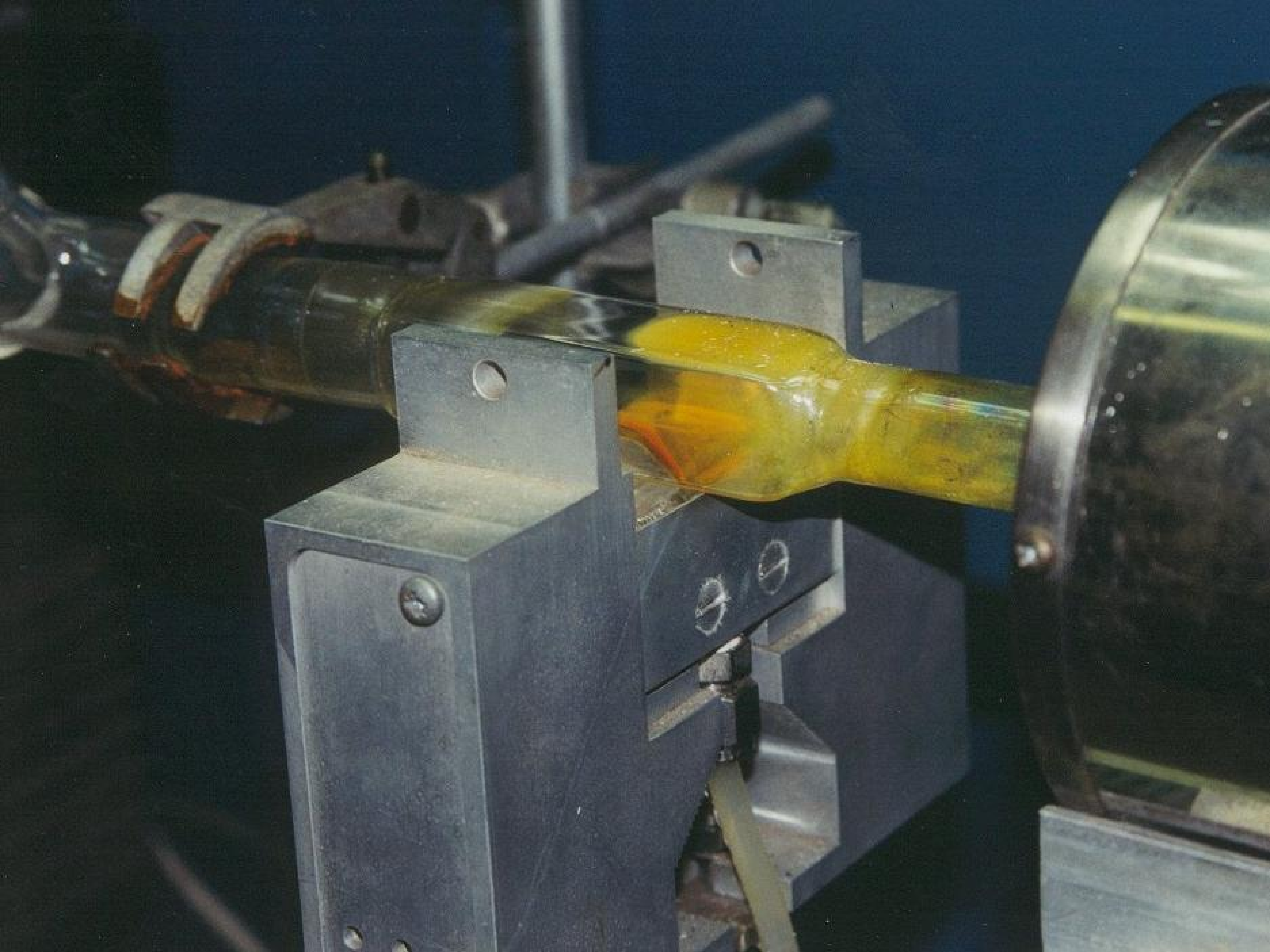
The CVD Process

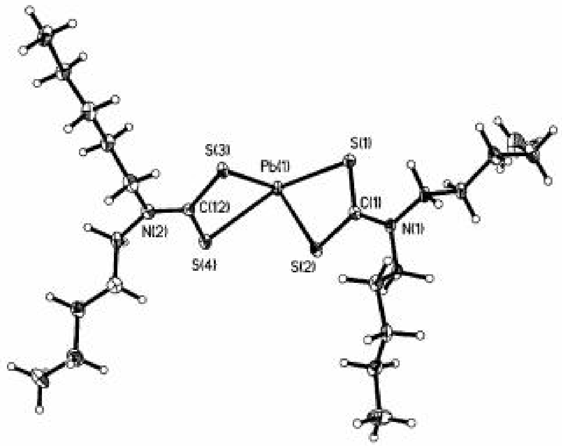


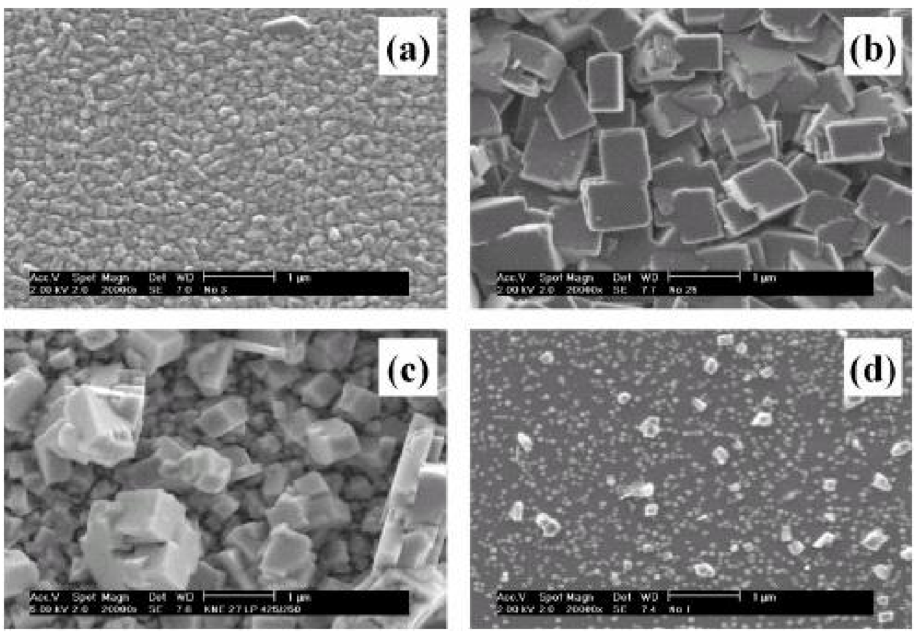




The AA-CVD Process







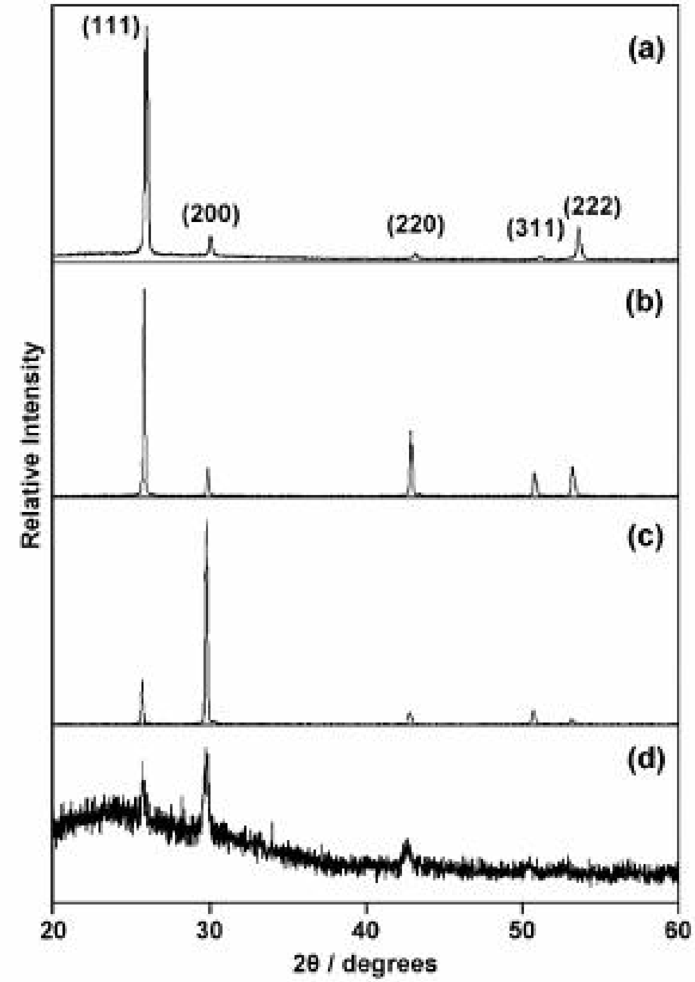
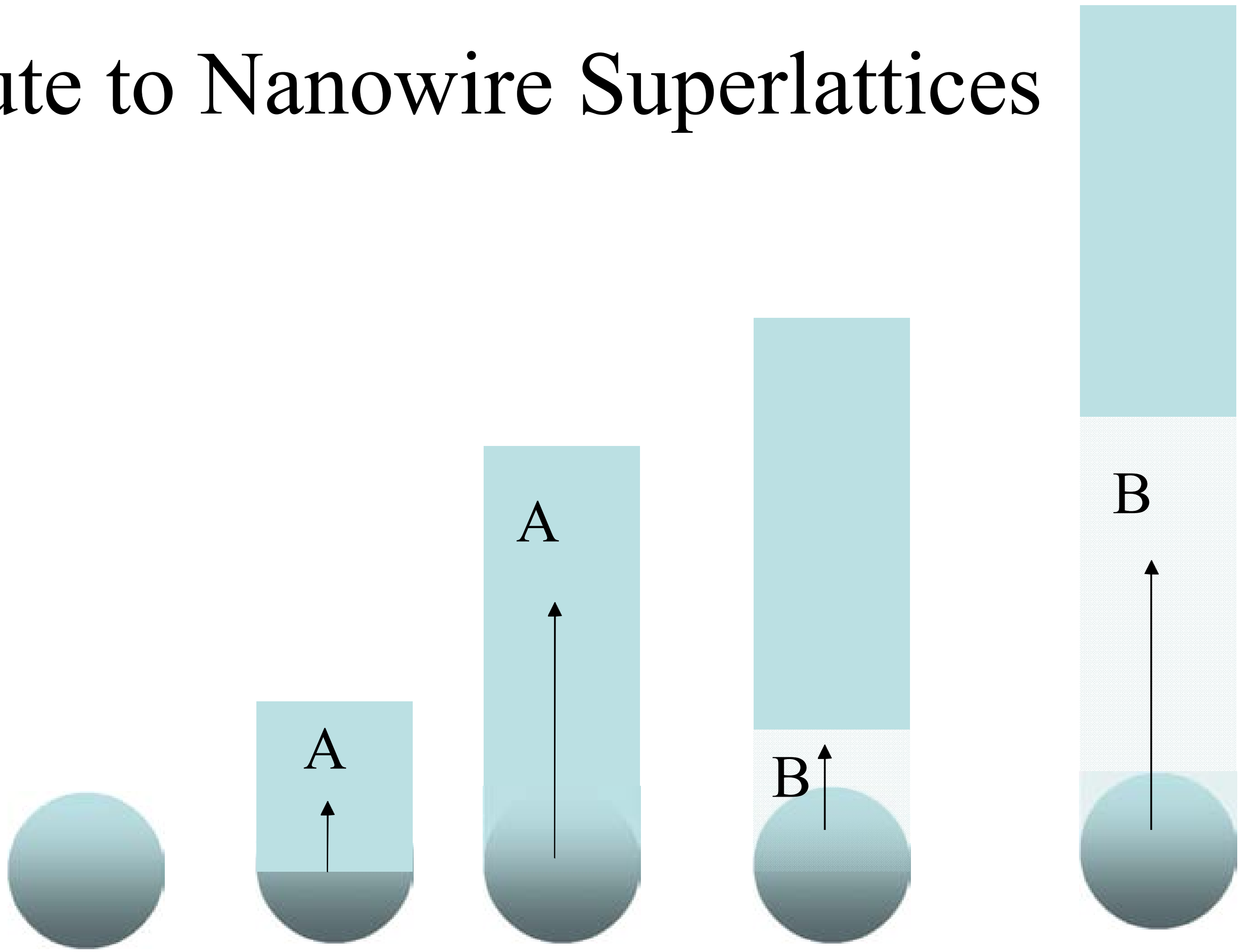


Fig. 4 XRPD patterns of PbS deposited from $[Pb(S_2CNEt^iPr)_2]$ by LP-MOCVD at (T_{prec}/T_{subs}) (a) 250/450, (b) 250/425 (c) 200/450 and (d) 200/425 °C.

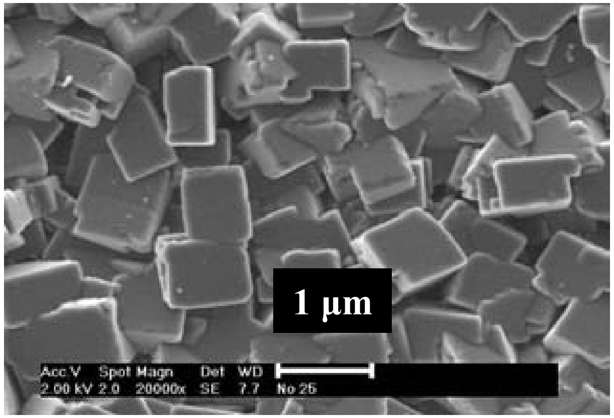
J. Mat Chem., 2004

A Route to Nanowire Superlattices



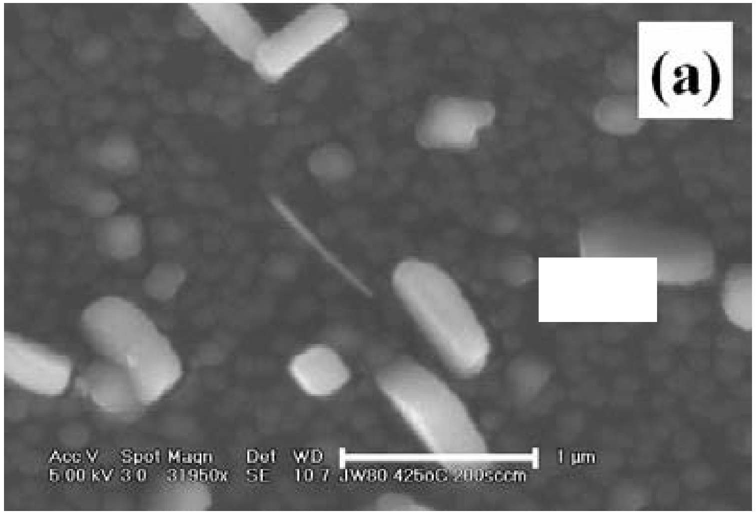
Growth of nanowire superlattice structures for nanoscale photonics and electronics:
M.S.Gudiksen, L.J.Lauhon, J. Wang, D.C. Smith and C.F.Lieber, Nature 415, 2002, 617-620

- Our previous studies on the growth of PbS thin films by AA and LP-MOCVD on glass and Si substrates, have lead to films comprising large (*ca.* 1 μm) cubic crystallites (Figure 2).



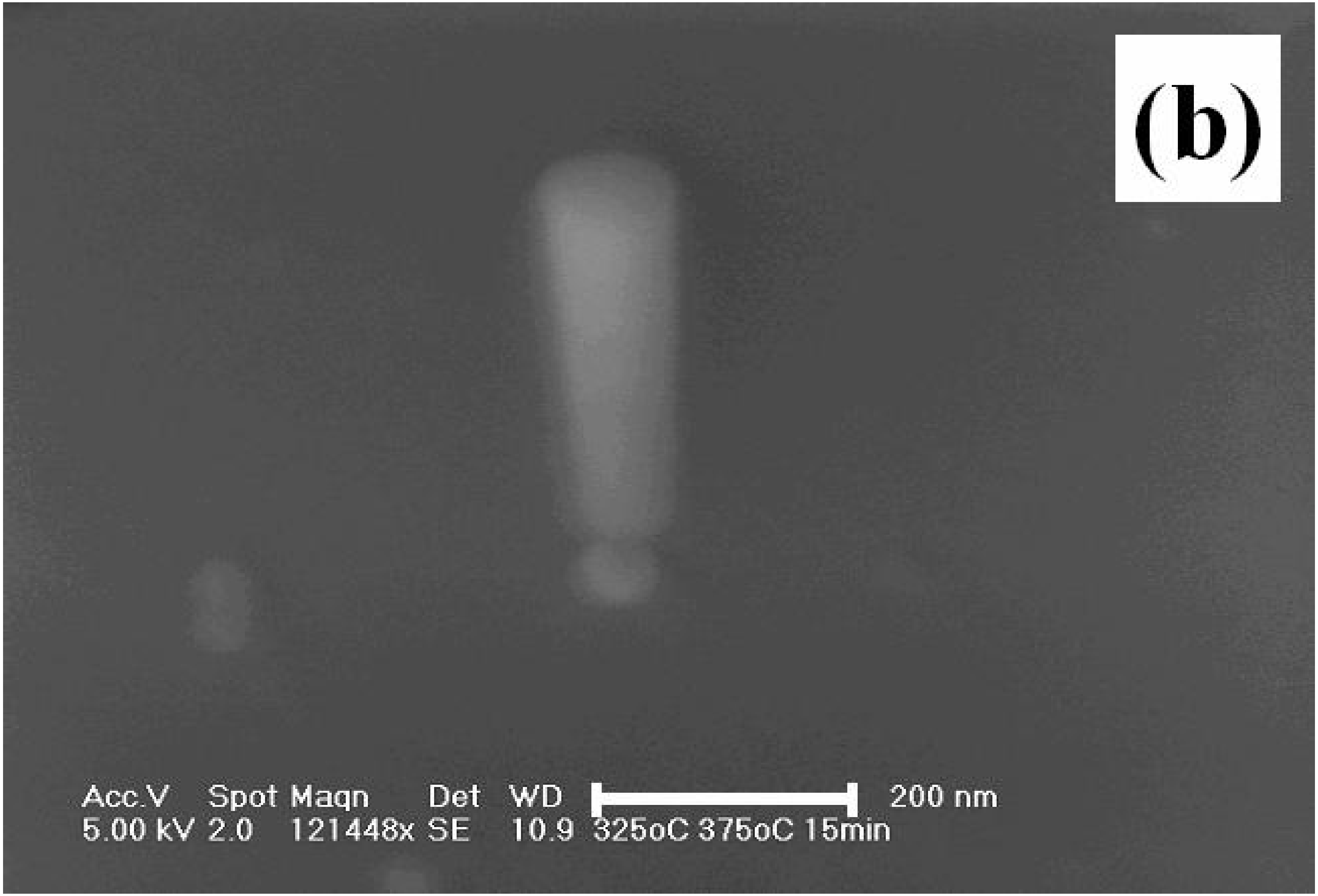
PbS films deposited on glass.

- Our present study, using Si substrates seeded with Au nanoclusters, *via* a custom made AP-MOCVD kit, has yielded films of radically different morphology
- (Figure 3).



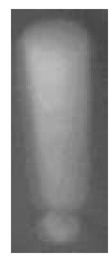
SEM images of PbS deposited at
(a) T_{prec} = 325 ^{o}C, T_{subs} = 350 ^{o}C,

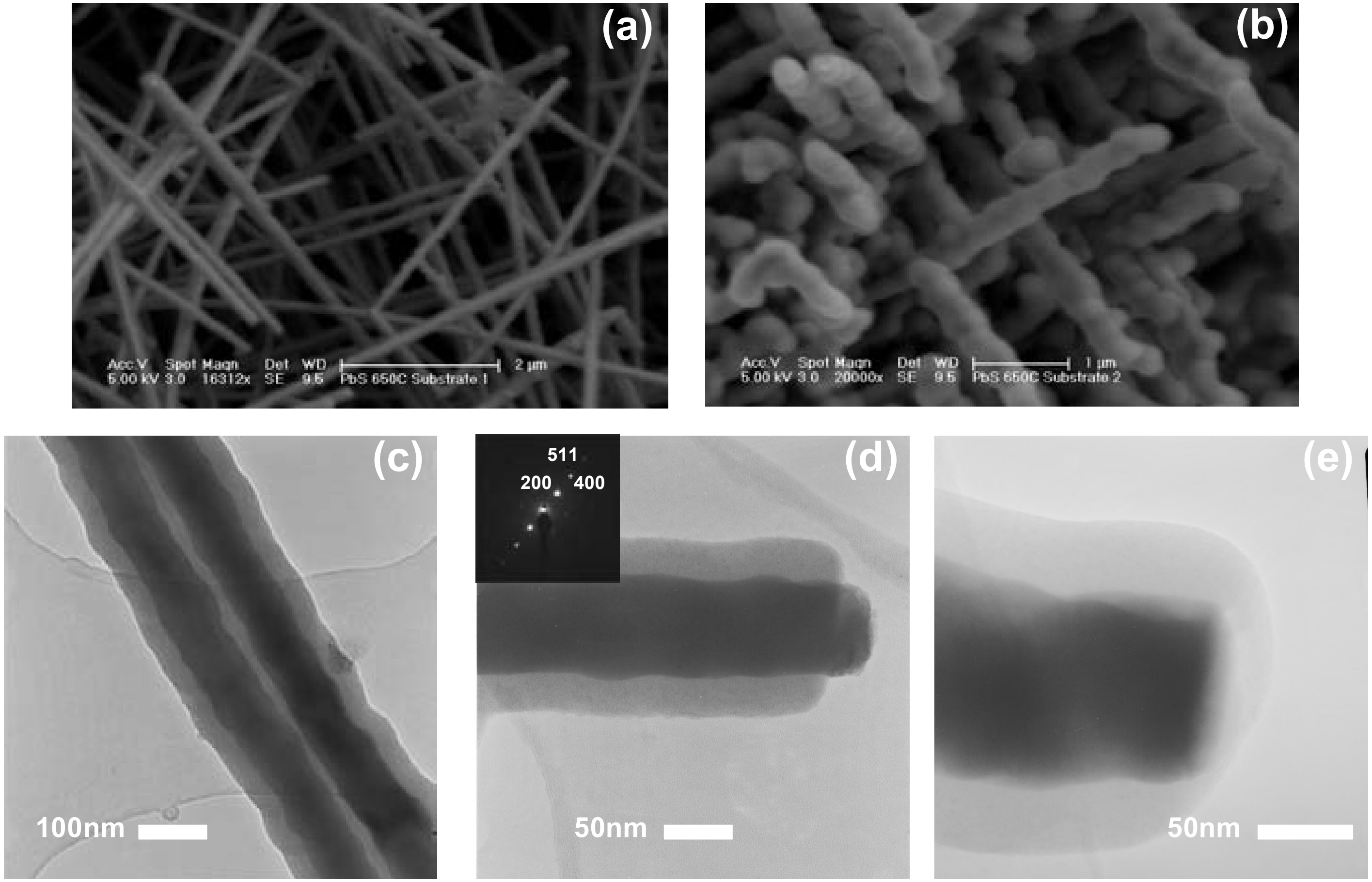
M. Afzaal, K. Ellwood, N. L. Pickett, P.O'Brien, J.Raftery, J.Waters J. Mater. Chem., 2004, 14, 1310


(b)
Acc.V Spot Magn Det WD 200 nm
5.00 kV 2.0 121448x SE 10.9 325oC 375oC 15min

Chemical Route to Punctuation

?

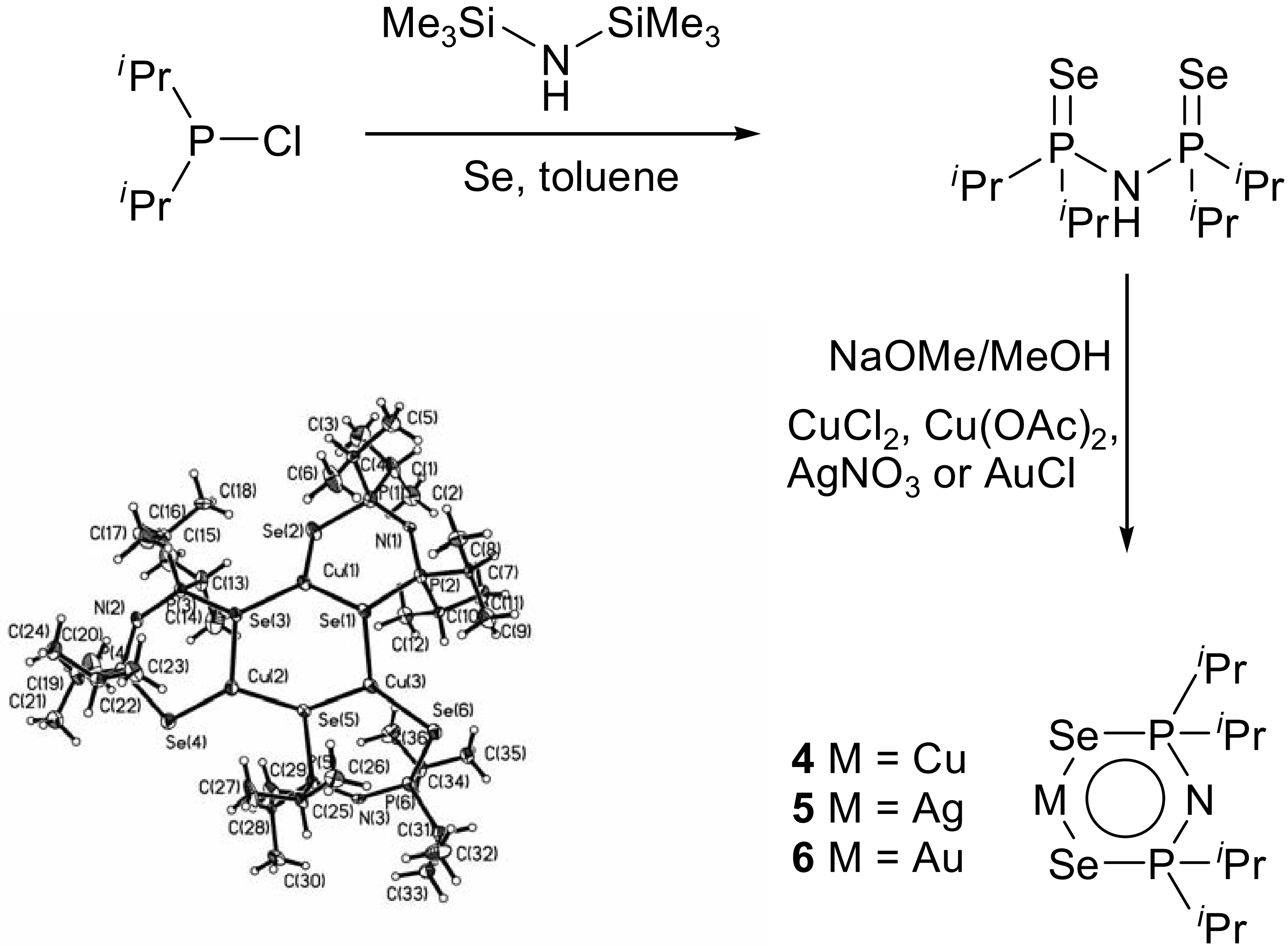




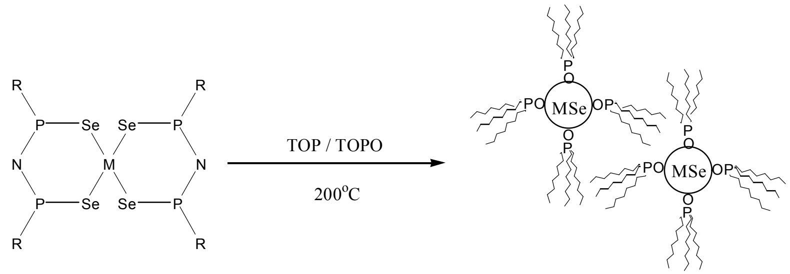
Silica coated PbS nanowires M. Afzaal and P.O'Brien

Journal of Materials Chemistry 2006 16, 113-115.

New Ways to Tellurides……..

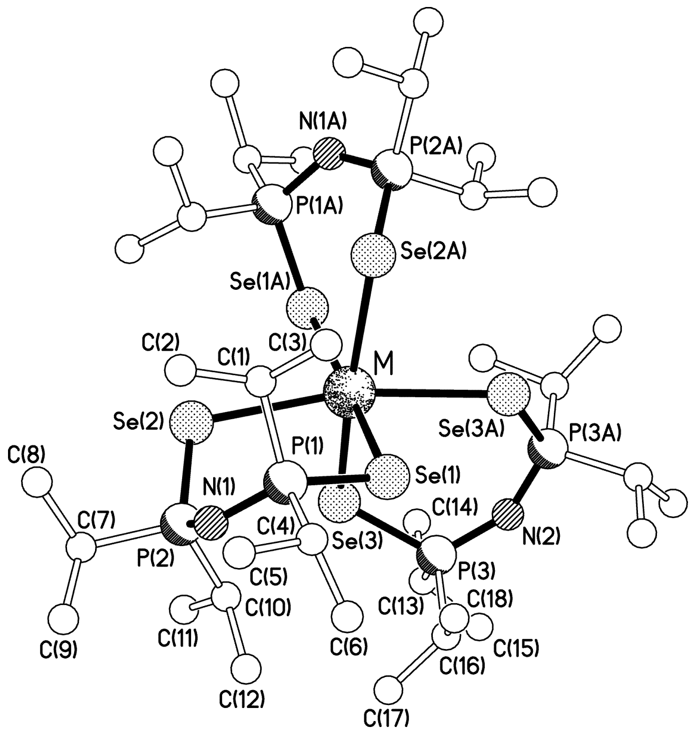


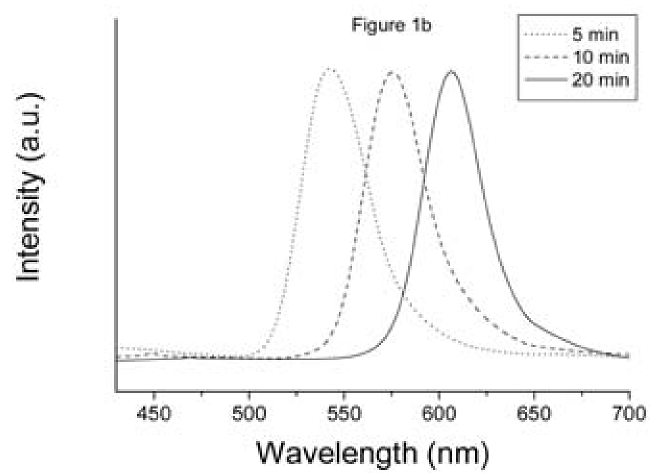
Imino-*bis*(diisopropylphosphine chalcogenide)



where R = ^{i}Pr or Ph and M = Cd, Zn or Hg

- Efficient synthesis of *"air-stable"* M $[N(SePR_2)_2]_2$ (yields 95-99%).
- Reaction can be scaled up (~25g) without loss to quality/yield.
- *"Dot"* synthesis is convenient and efficient.





PL of CdSe by Thermolysis of $Cd[N(SeP^{i}Pr_2)_2]_2$

D.J.Crouch, P. O'Brien, M.A.Malik, P.J.Skabara and S.P. Wright, Chem. Commm., 2003 1454.

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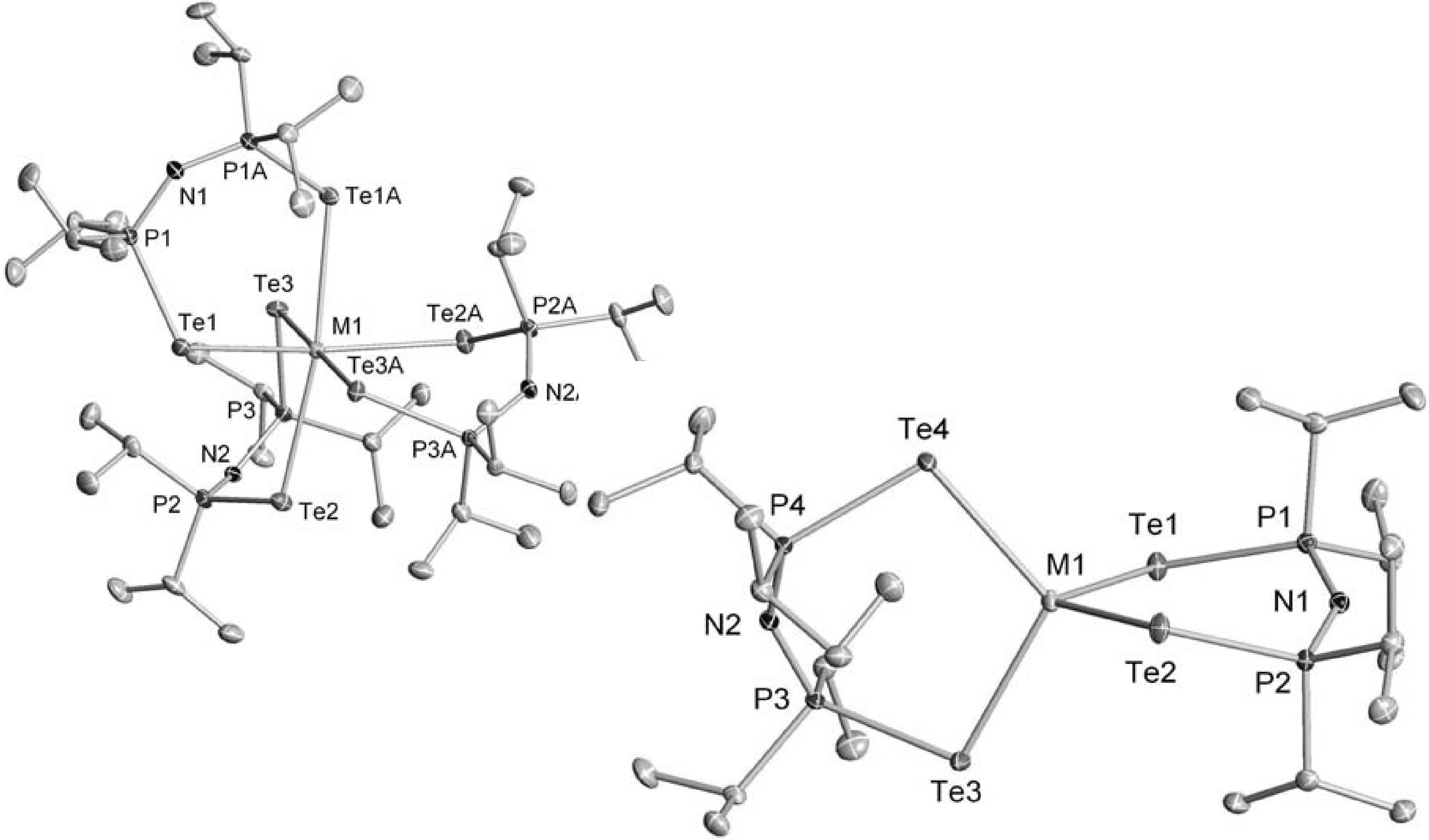
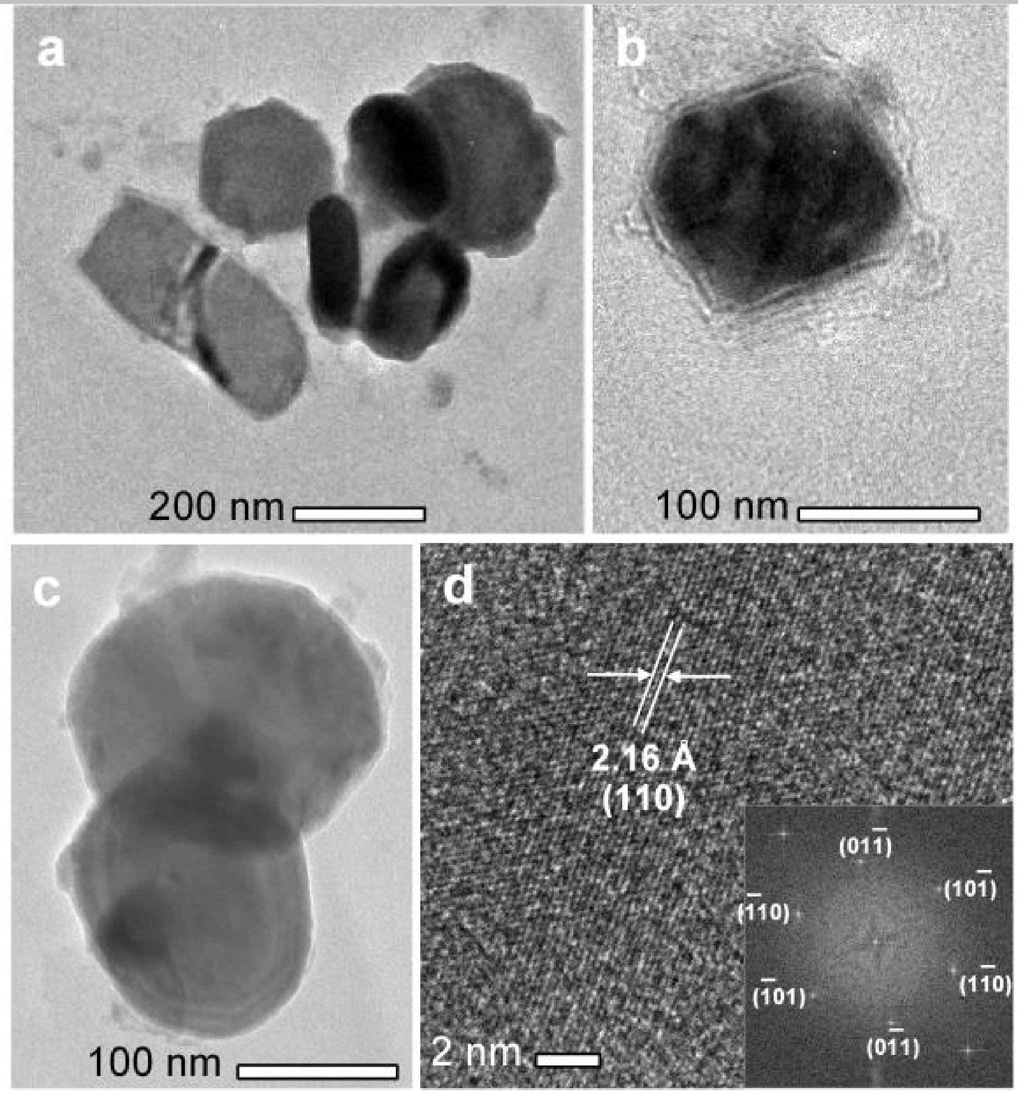


T. Chivers, DJ. Eisler, JS Ritch, Dalton Trans. 2005, 2675.

TEM Pictures of Sb_2Te_3

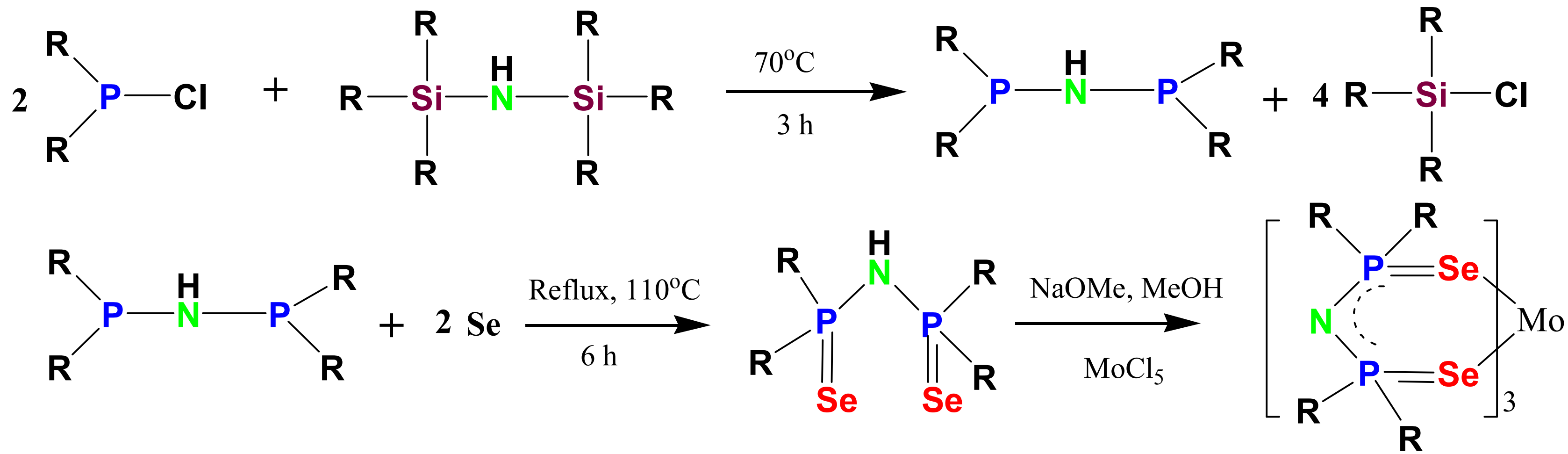


HRTEM and FFT (inset) of the films grown at 475 ºC

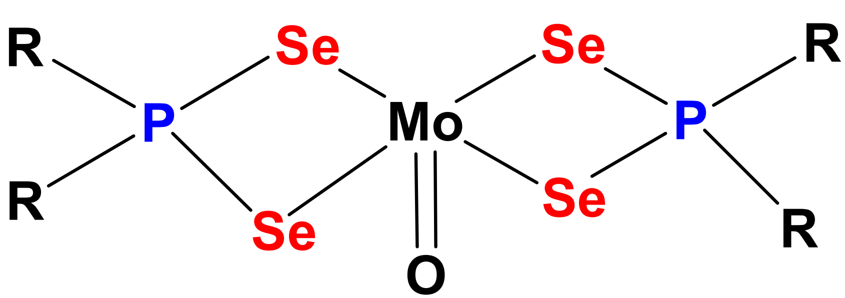
J. Amer. Chem.Soc. 2006, 128, 3121-3122

Just when you thought you understood!

Mo Complex from Woollins' Reagent

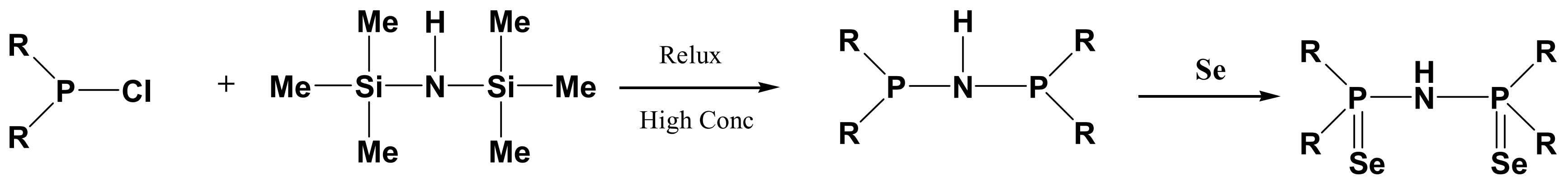


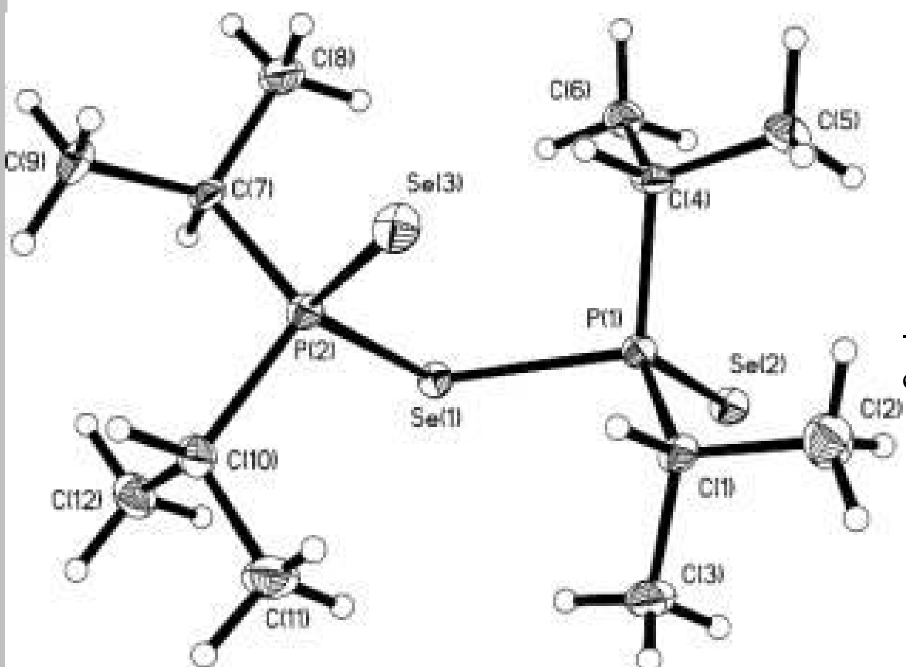
Obtained product

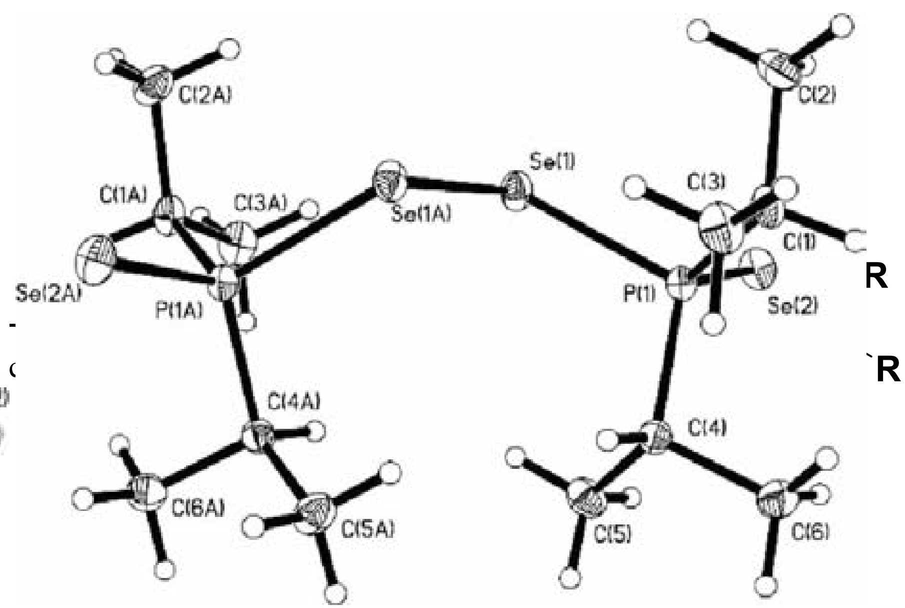


May not get Wollins Reagent, but the "Wrong Ligand"

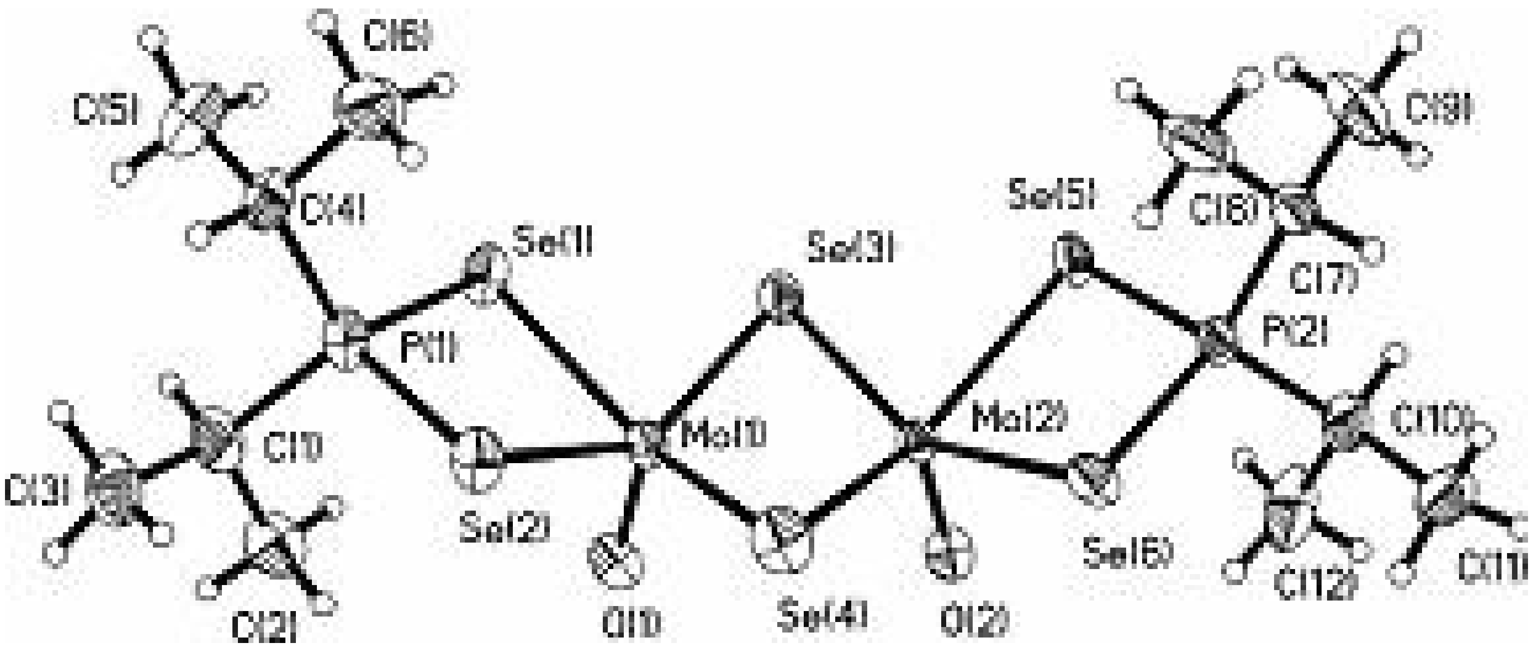
MAIN PRODUCT







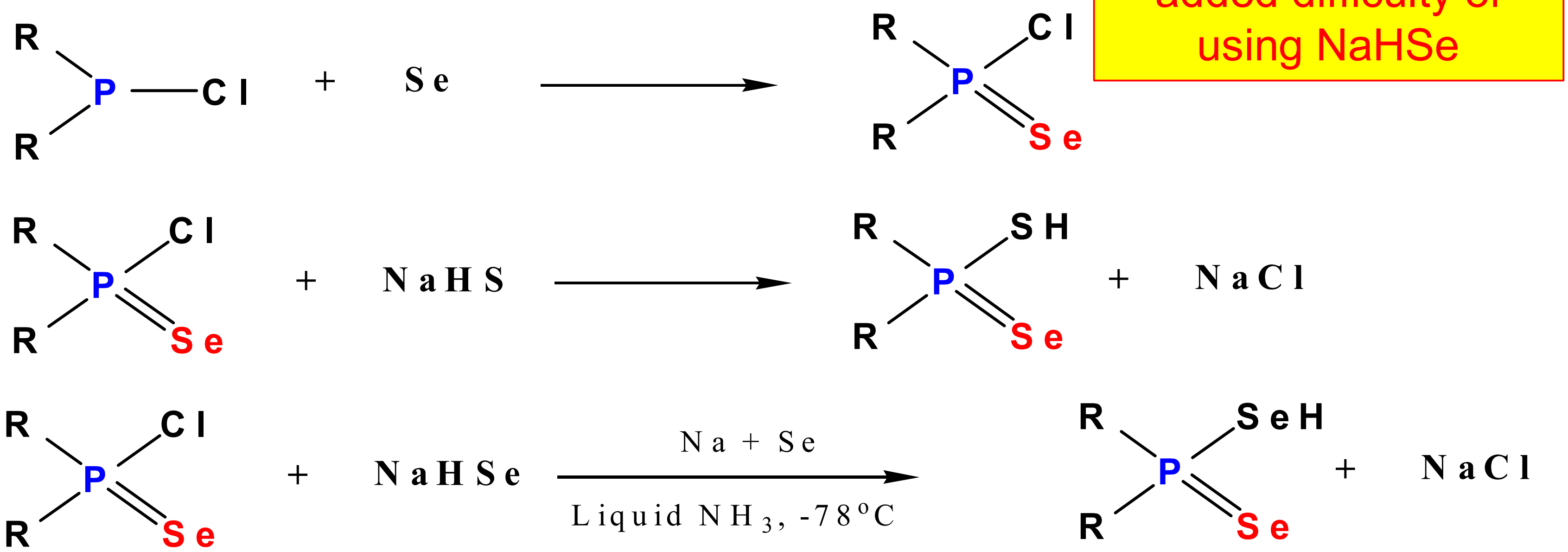
$[Mo_2O_2Se_2(Se_2P^iPr_2)_2]$ $MoCl_5$ and$[^iPr_2PSe]_2Se$



DIALKYLDICHALCOGENOPHOSPHINATES

Previous Work

Not-reproducible with added difficulty of using NaHSe

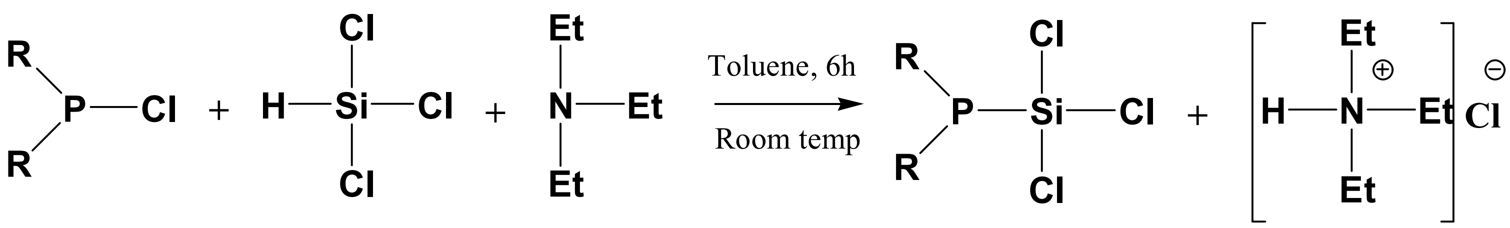


Unstable, never isolated, used *in situ* to make metal complexes, no solid state characterization

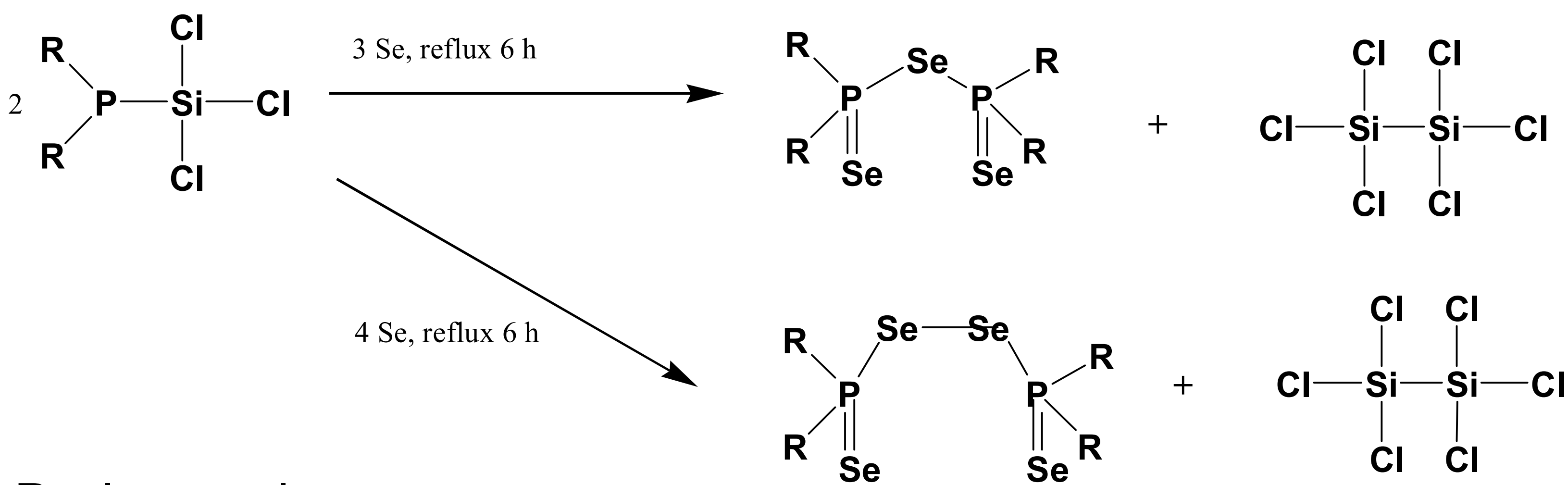
*References: (a) J. Inorg. Nucl. Chem. 1974, **36,** 472-5; (b) Angw. Chem. 1969, 8, 89. (c) Polyhedron 1991, 10, 2641.*

Novel Synthetic Route *(1)*

STEP 1: BENKESER REACTION



STEP 2: INSERT Se

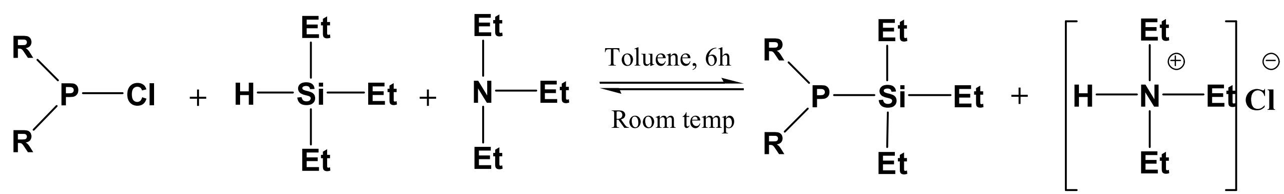


R = Isopropyl

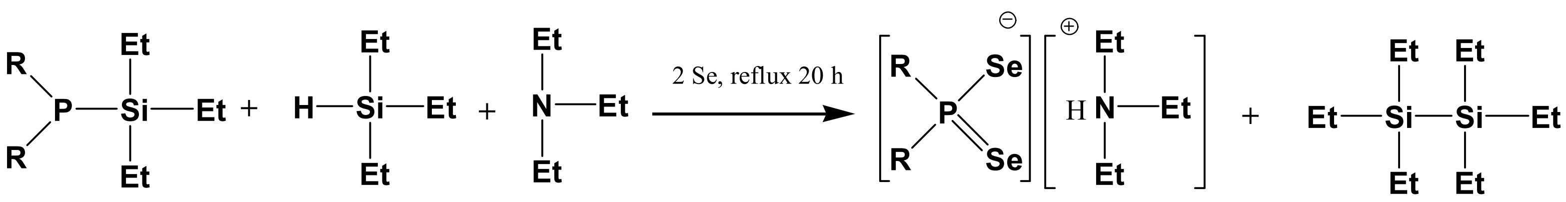
Novel Synthetic Route *(2)*

- Alternatively, use excess Lewis Base NEt_3 to stabilize ionic species e.g. $[(^iPr)_2PSe_2]$
- $HSiCl_3/NEt_3$: did not work due to the formation of $[HNEt_3^+][SiCl_3^-]$
- $HSiEt_3/NEt_3$: worked

STEP 1: BENKESER REACTION

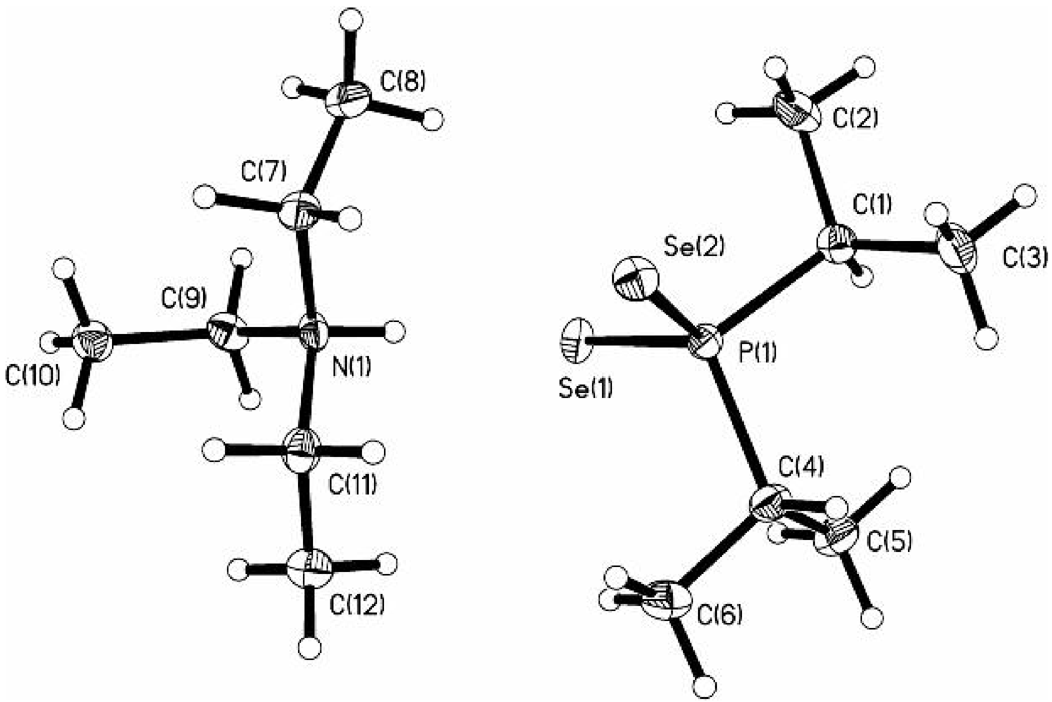


STEP 2: INSERT Se



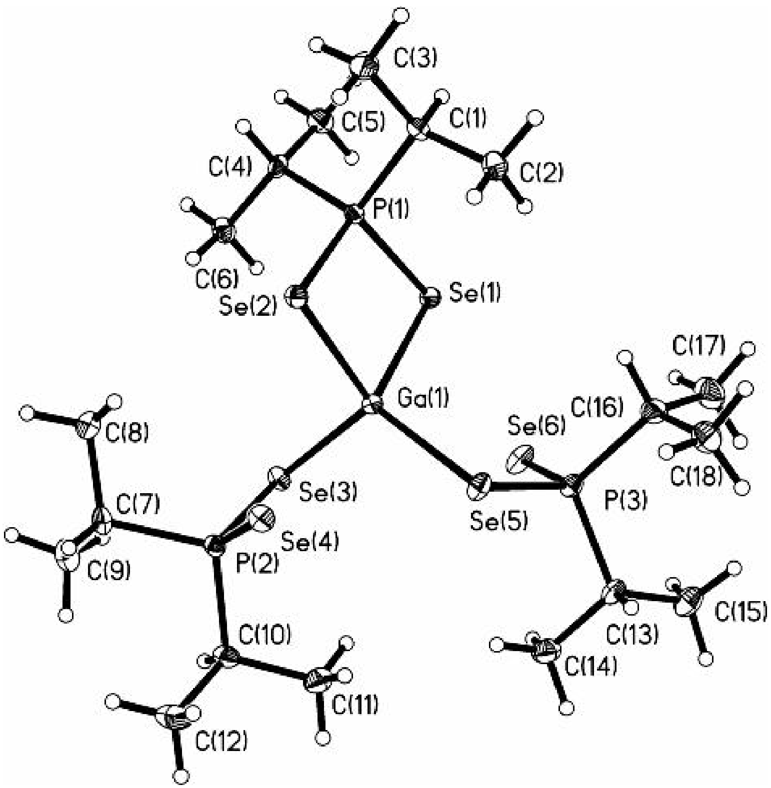
R= Isopropyl; Phenyl

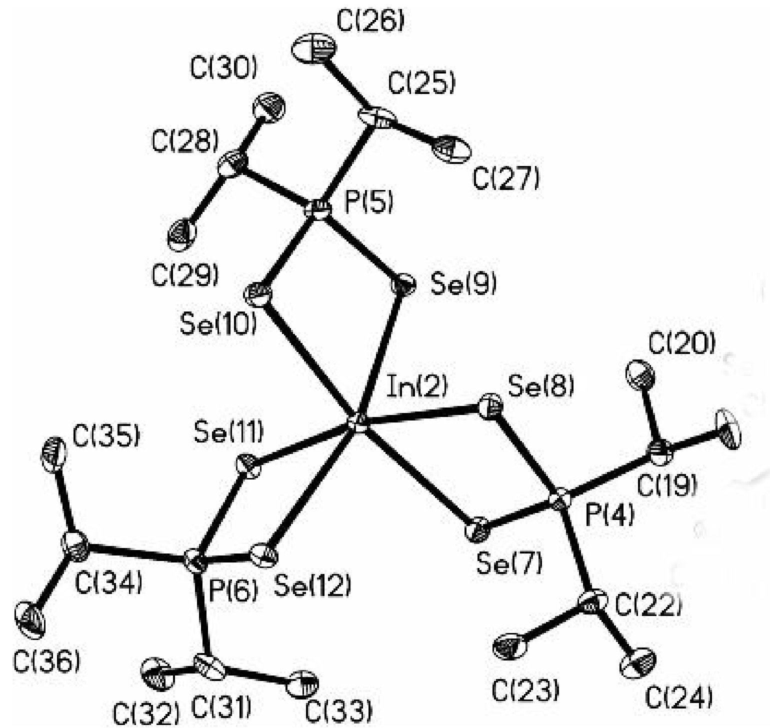
Crystal Structures



$[^iPr_2PSe_2][HNEt_3]$ Yield = ~ 85%

Group 13 complexes

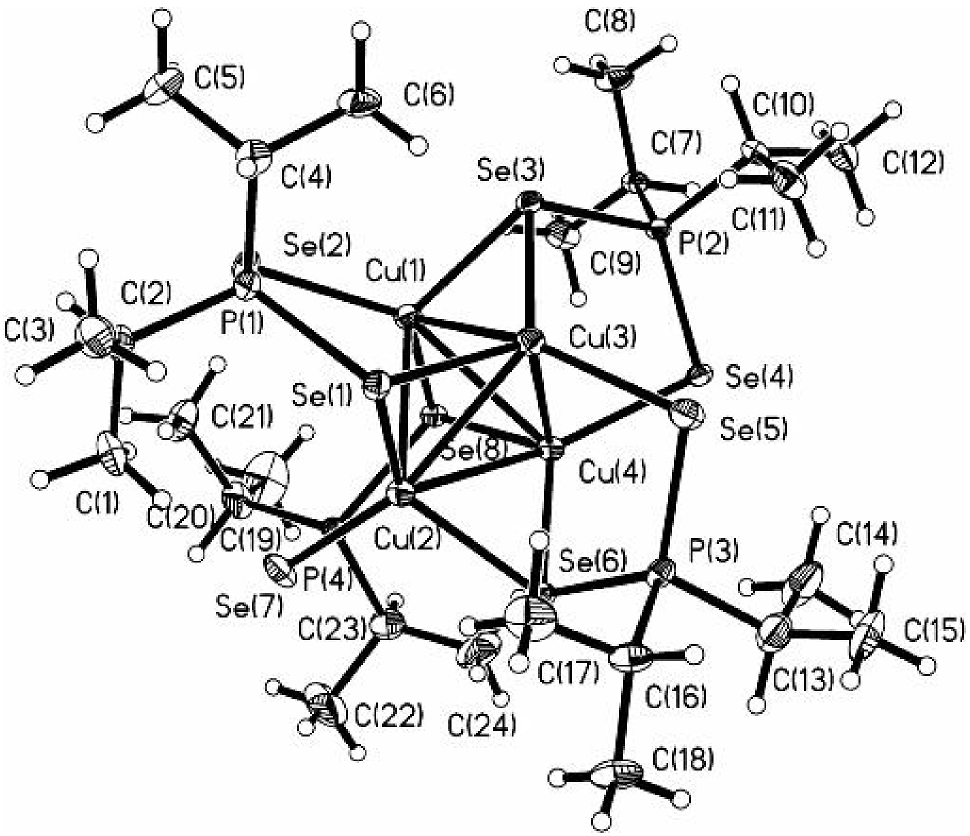


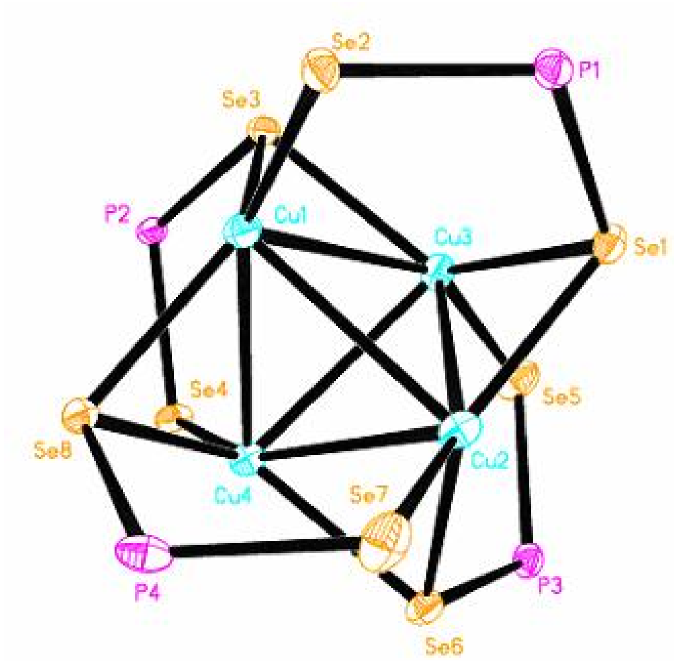


$$n\,[R_2PX_2]^- \quad + \quad M^{n+} \xrightleftharpoons[\text{Room Temp.}]{\text{MeOH}} [R_2PX_2]_nM$$

$R = Ph; {}^iPr$ $\quad X = S; Se$ $\quad M^{n+} = In^{3+}; Ga^{3+}$

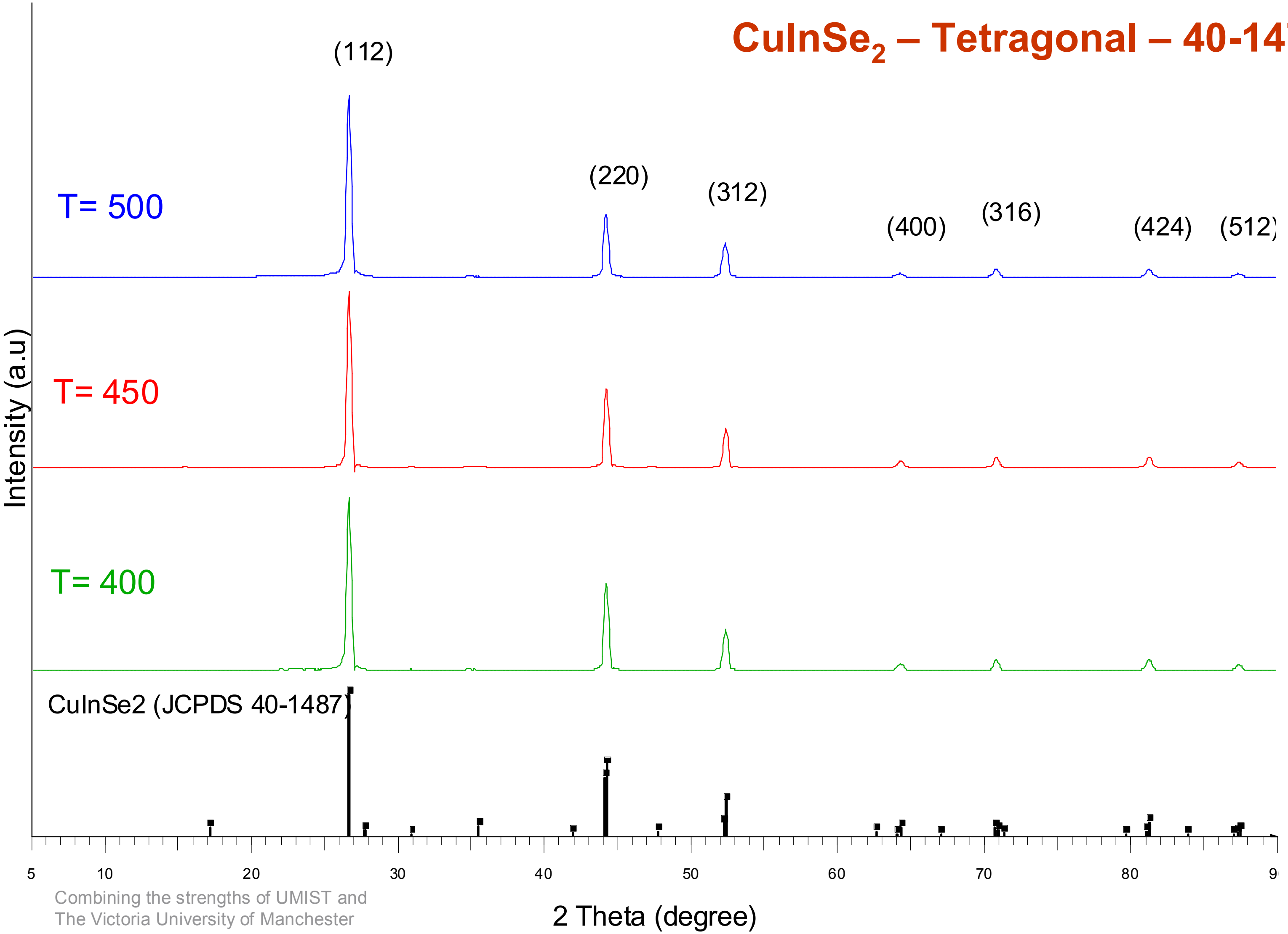
Cu - Precursor



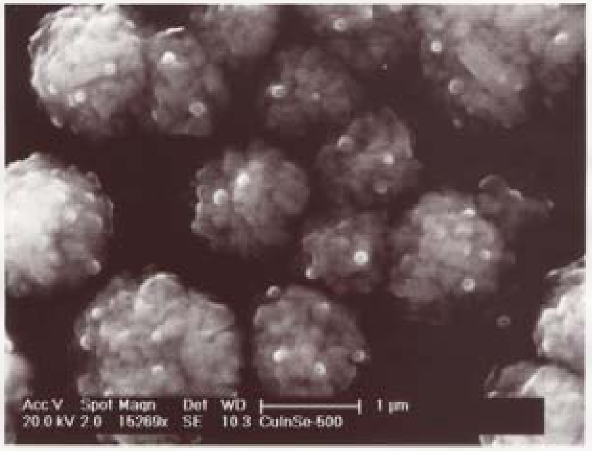


$C_{24}H_{56}Cu_4P_4Se_8$, Mr =1354.41, Monoclinic, space group P2(1)/n, a = 12.9380(16)Å, b = 17.527(2) Å, c = 18.617(2) Å, ♋ = 90, ♌ = 91.453(2), ♑ = 90, V = 4220.3(9) Å^3, Z = 4, ❒calculated = 2.132 g cm-3, ❍ = 9.056 mm^{-1}, T = 100(2) K. Crystal size 0.35 x 0.30 x 0.2 mm, ● = 0.71073 Å, R1= 0.0309, wR2 = 0.0590 .

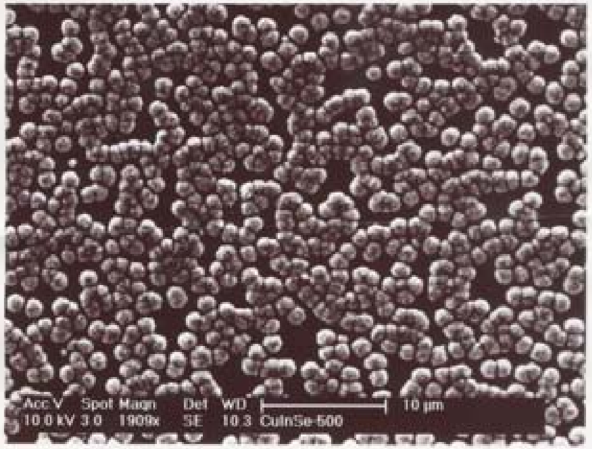
CuInSe

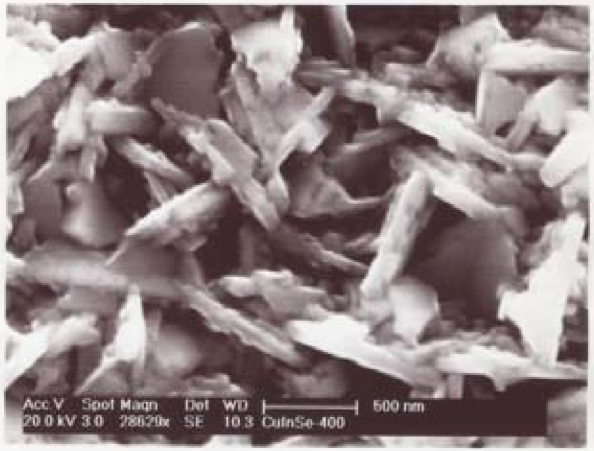

CuInSe$_2$ – Tetragonal – 40-1478
(112)
(220)
(312)
(400)
(316)
(424)
(512)
T= 500
T= 450
T= 400
CuInSe2 (JCPDS 40-1487)
Intensity (a.u)
5
10
20
30
40
50
60
70
80
9
2 Theta (degree)

SEM

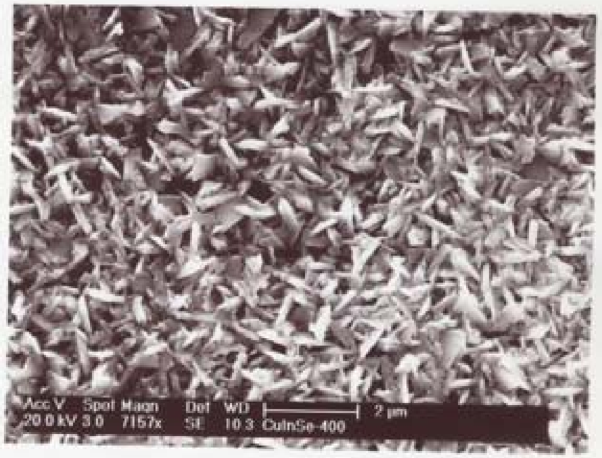


T = 500°C

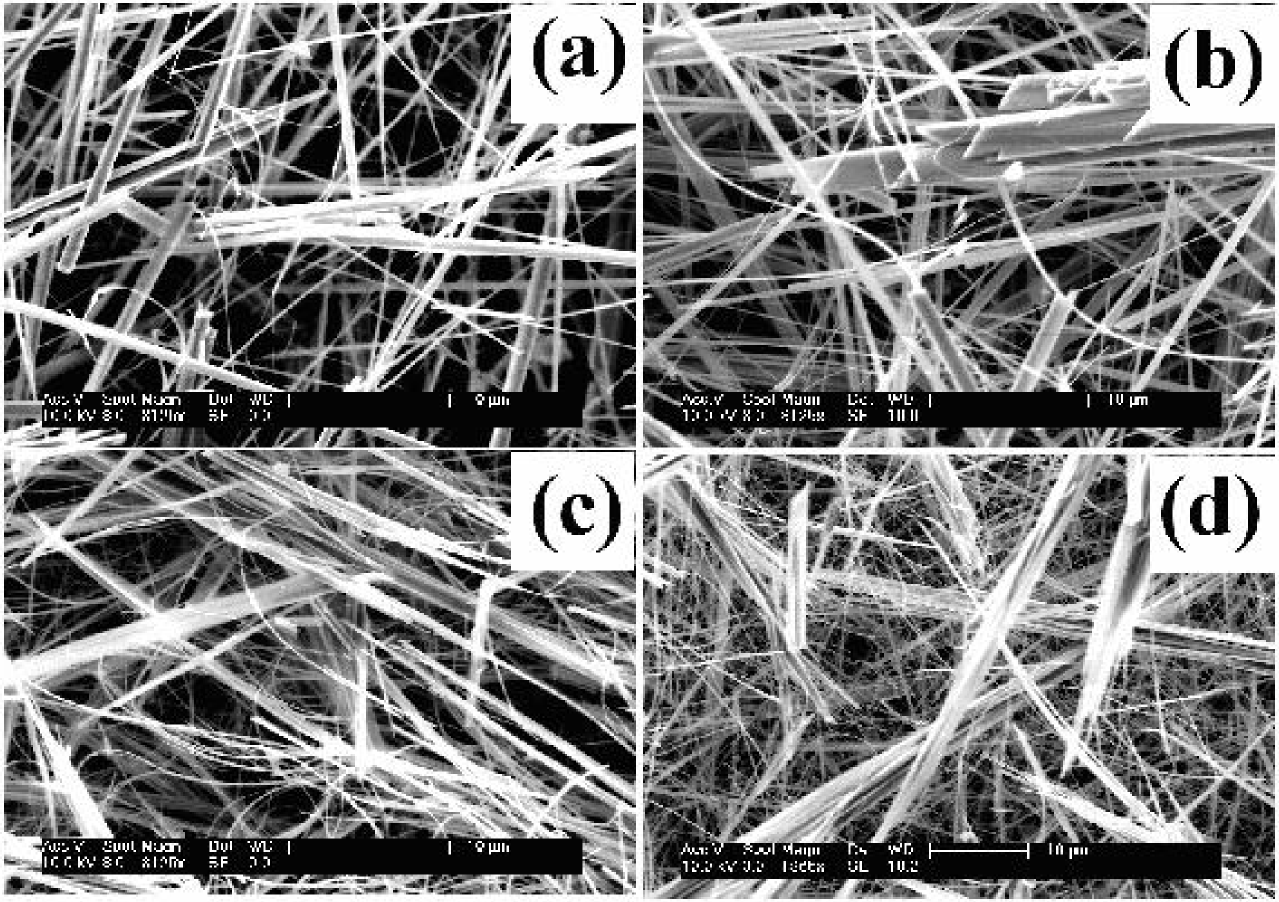




T = 400°C



EDX	
Element	% Atom
Cu	23.63
In	23.36
Se	50.92
P	2.09



Micrograph of rhobohedral Sb_2Se_3 grown on glass at

(a) 400 °C (b) 425 °C (c) 450 °C (d) 475 °C from

(b) $[Sb(Se_2P^iPr_2)_3]$ with an Ar flow rate of 180 sccm

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Structure of Talk

- Why now ?
  - Looking at some nanodimensional objects by way of introduction
- Synthetic approaches semiconductors
- How nanoparticles grow and rods and tetrapods
- Other materials a rogues gallery
- What are some of the opportunities
  - The Nanoco Technologies Ltd perspective
- Closing remarks

NANOCO
TECHNOLOGIES

illuminating* *the future

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Company overview

- **World leading technology company**
  - Produce fluorescent semiconductor nanoparticles "quantum dot“ and quantum dot products
- **Patented technology solves problem of producing high quality quantum Dots on a large scale**
- **Strategic partnerships with Application Developers**
  - **Tailored solutions to incorporate quantum dots into commercial applications**
- **Quantum Dots are a “platform technology” with many applications in different industry sectors**
- **Developed a range of quantum dots acceptable for commercial use**
- **Nanotechnology Spin-out company from University of Manchester, UK**

A True Platform Technology

What are Quantum Dots?

- Semiconductor material 100,000 x smaller than the width of a human hair
- Size gives unique electronic and optical properties
- Platform technology with many applications across different industry sectors

Why use them?

- Replacement for luminescent dyes and inorganic materials
- Better optical and electronic efficiencies
  - More stable
  - More versatile
- True platform technology which can be utilized in a range of applications across different industries

Nanoco Solves "Scale up" Problem

The Problem

The existing quantum dot 'manufacturers' processes are

- Complex
  - Hazardous and used banned substances
- Costly
- Low manufacturing yield
  - No-one can produce a 1g batch

Without stable, cost effective supply of larger quantities of quality QD, developers are unable to bring there applications to market

The Solution

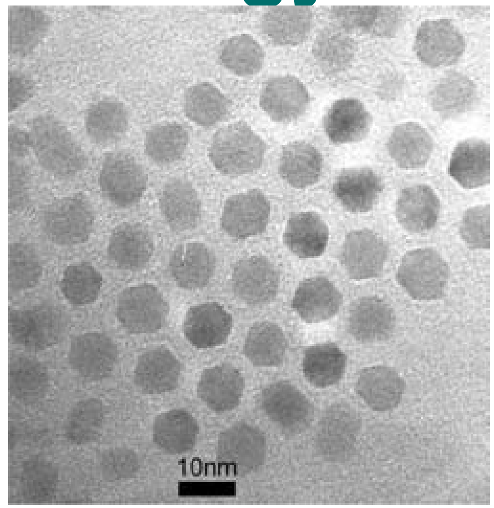
Nanoco's patented technology can

- Using a 'simple' and controlled process
- At a low cost
- Now regularly produce r+d batches of 100g

Nanoco also has world leading patent technology to unlock the market

Nanoco's Technology

High resolution electron microscope Image of single QD (5nm across)

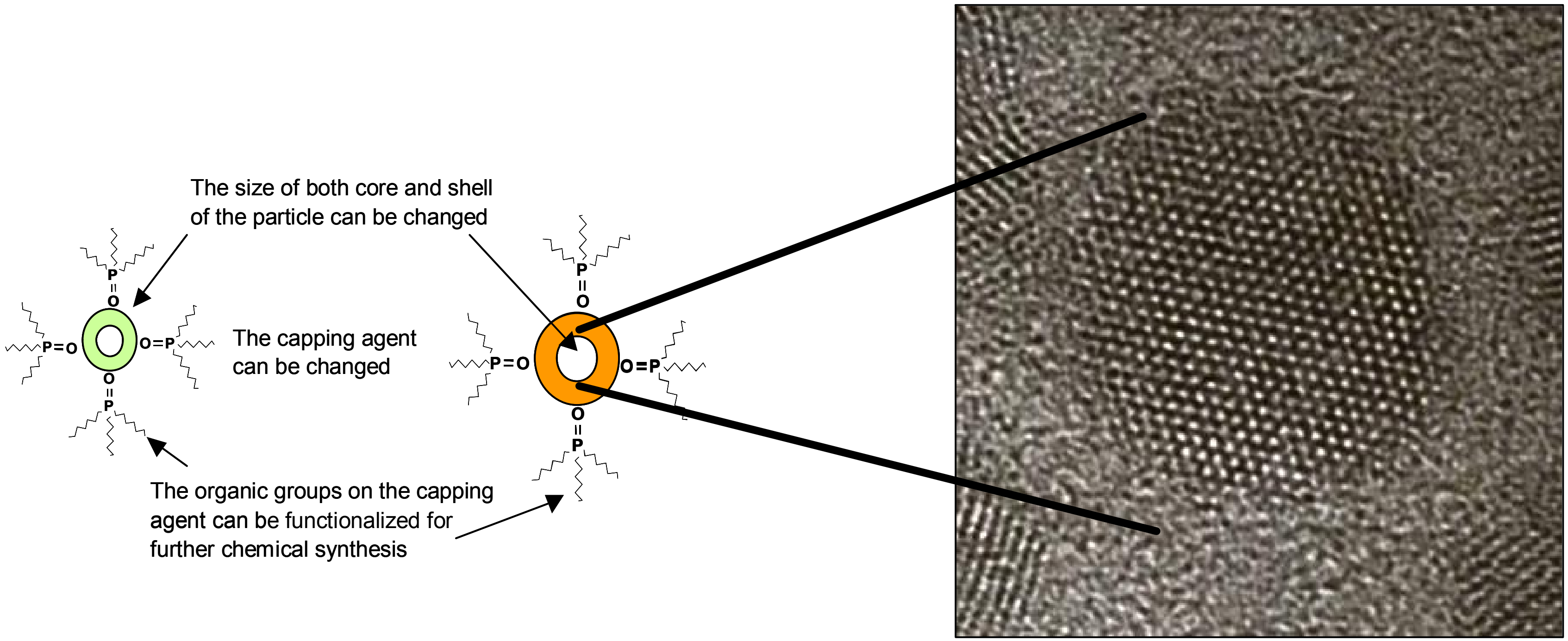


Electron microscope image showing QD In very ordered patern

30 grams of 560nm QD. No other company in the world can produce this quantity. Market value in today's bio applications greater than $10Million. Competitors can only produce 100 milligrams, 300X less material per batch. Nanoco will soon be producing 1 kilo batches

Dilute solution QD excited by UV light

What are Quantum Dots?



High-resolution transmission electron microscopy image showing the lattice plans of a nano-crystalline Quantum Dot, measuring 5nm across (80,000 times smaller than the width of a human hair)

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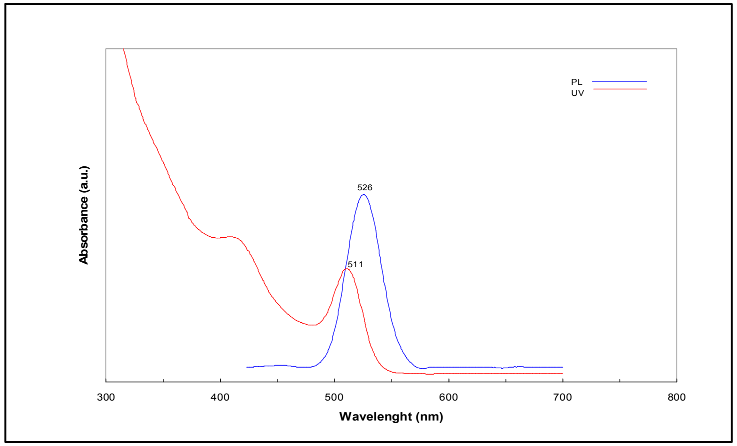
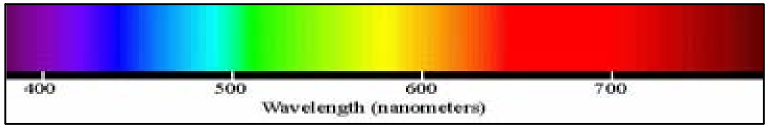


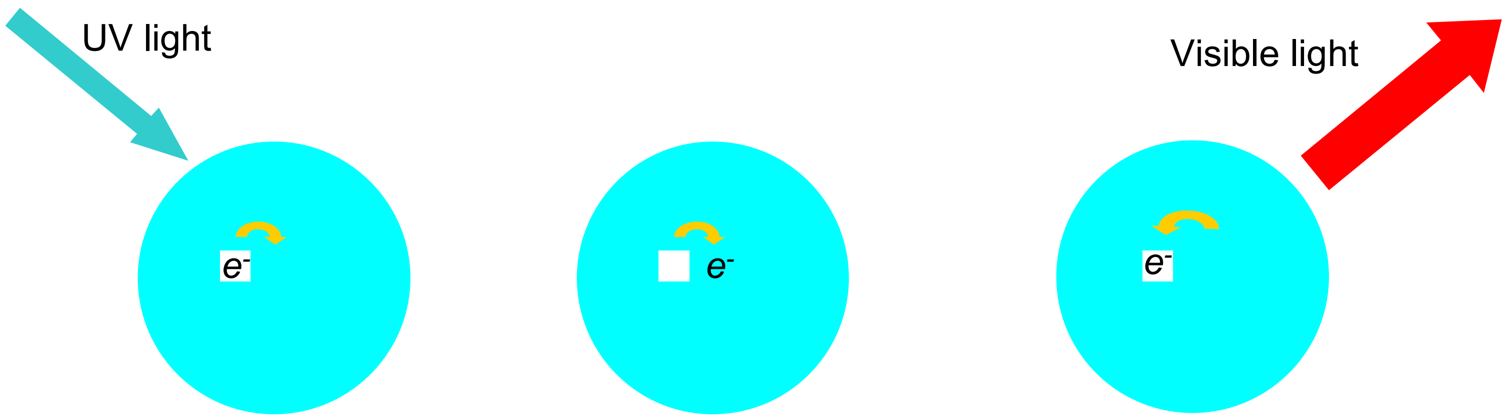


- **Quantum dots absorb light over a wide wavelength range but have narrow emission spectra.**
- **The solutions, all contain the same semiconductor material (CdSe) but are different colours because unlike bulk CdSe, when below a certain size limit, we can control the electrical properties of the particles, by simply changing their size.**

What are Quantum Dots?

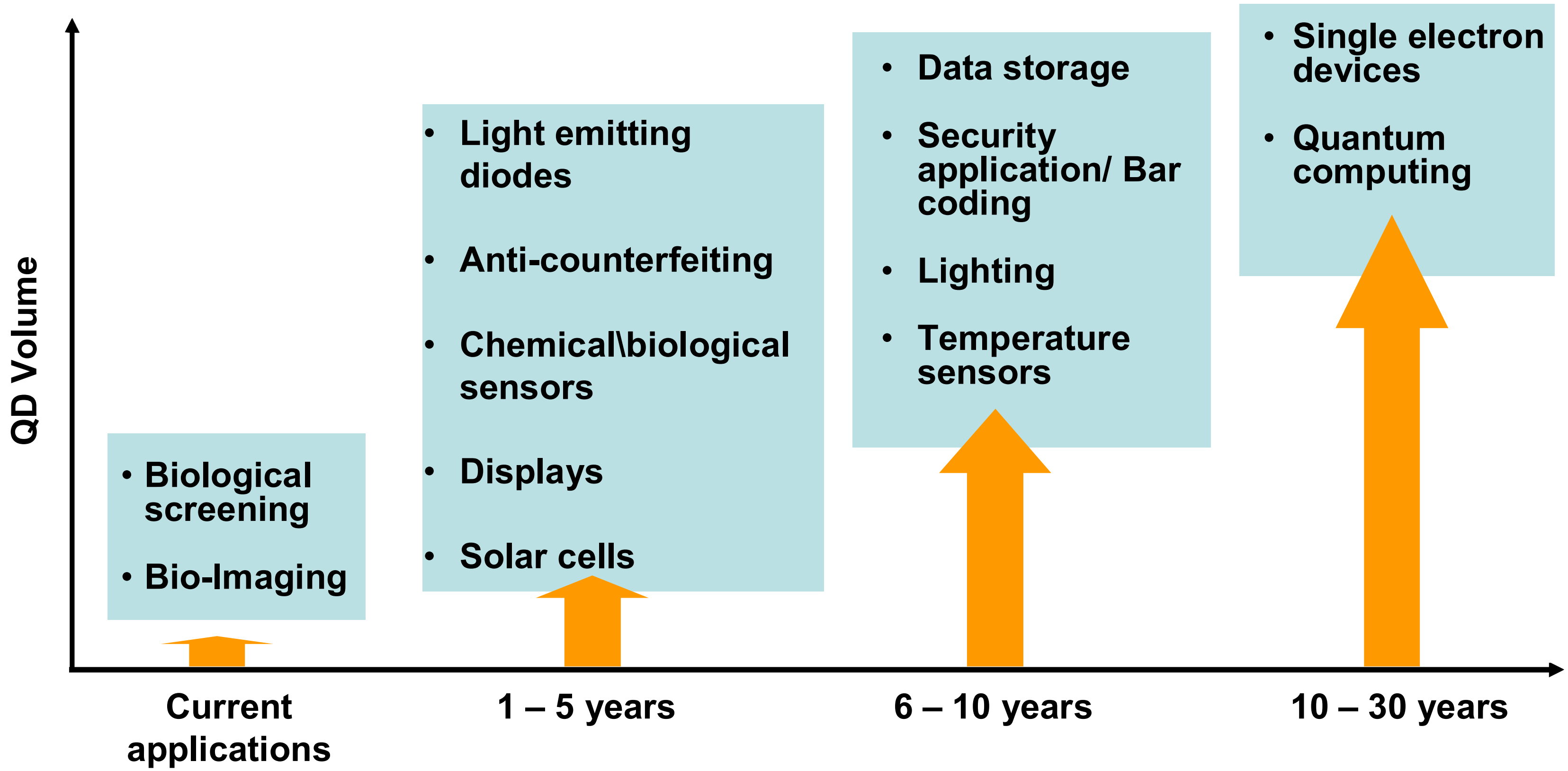
How Quantum Dots Work

- UV light excites QD and kicks out electron creating electron and a vacant hole
- As electron relaxes back into the hole a photon is emitted (visible light)
- Size quantization effect – wavelength emitted depends on physical size of the quantum dot



UV light excites QD | kicks out electron | electron relaxes back into hole

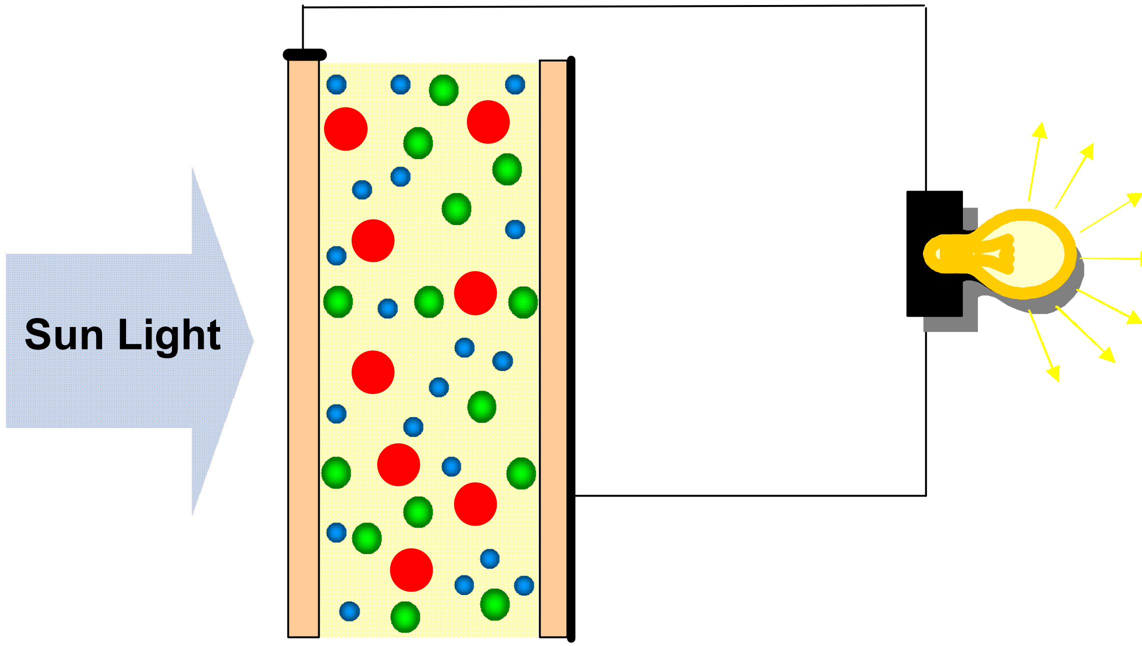
Quantum Dot Applications



Nanoco's technology is allowing the QD market to grow rapidly

QD Solar Cell Devices

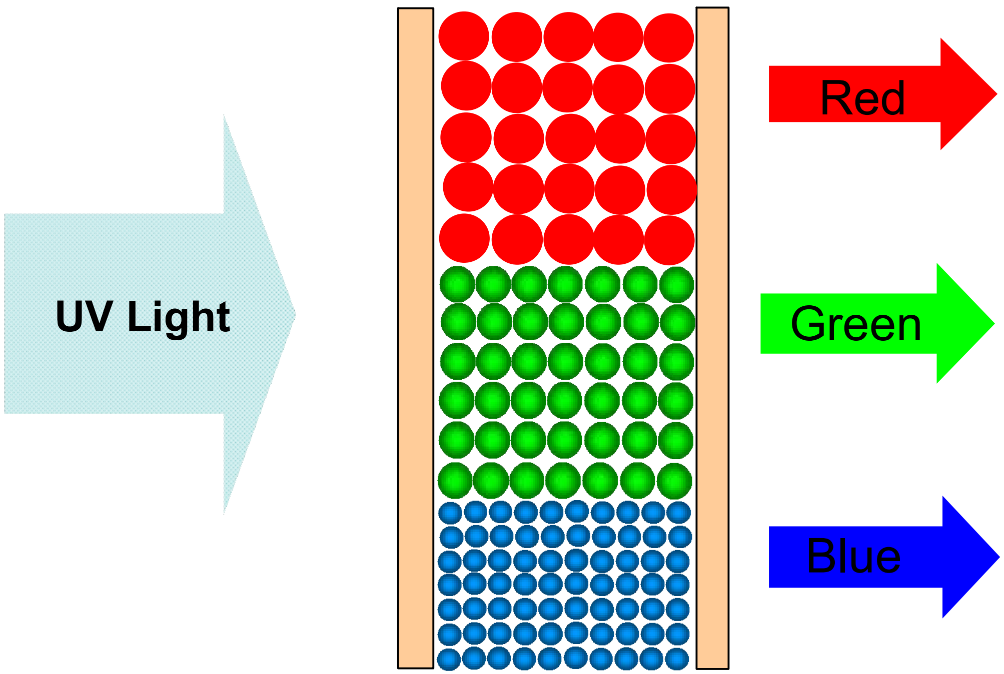
- Capture full spectrum of radiation
- Quantum dots can be processed into inks
- High efficiency of quantum dots
- Tune the quantum dots to the radiation that you want to capture



Applications: Plastic solar cells, Gratzel cells, Solar roof tiles

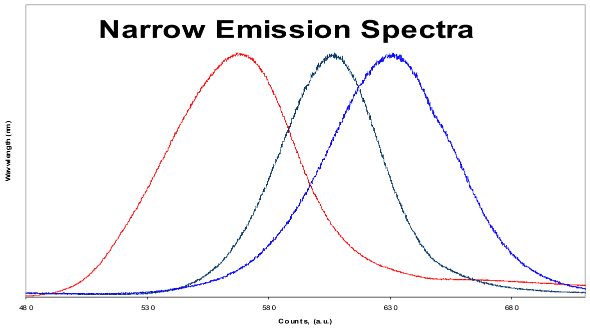
Displays and QD-LED's

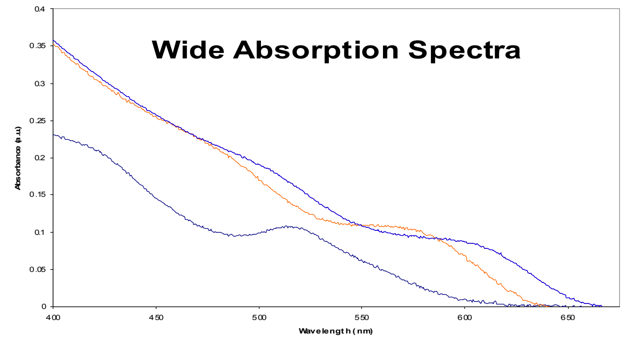
- Low energy consumption,
- Same material for all colours,
- High efficiency

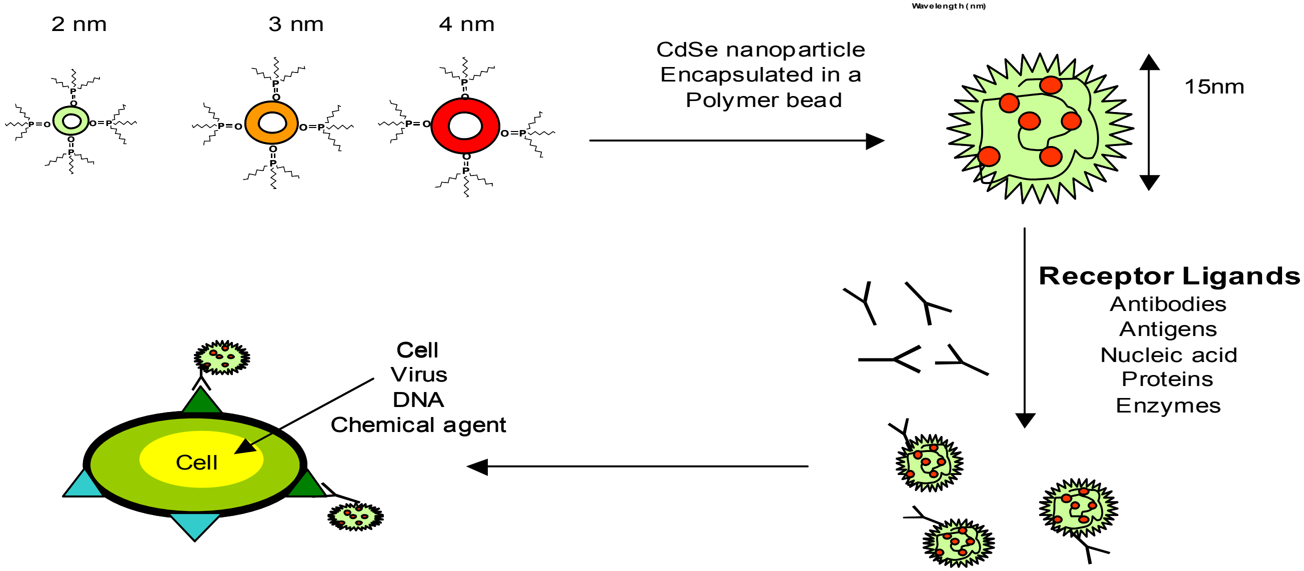


Make full colour displays made by using quantum dots for each primary colour

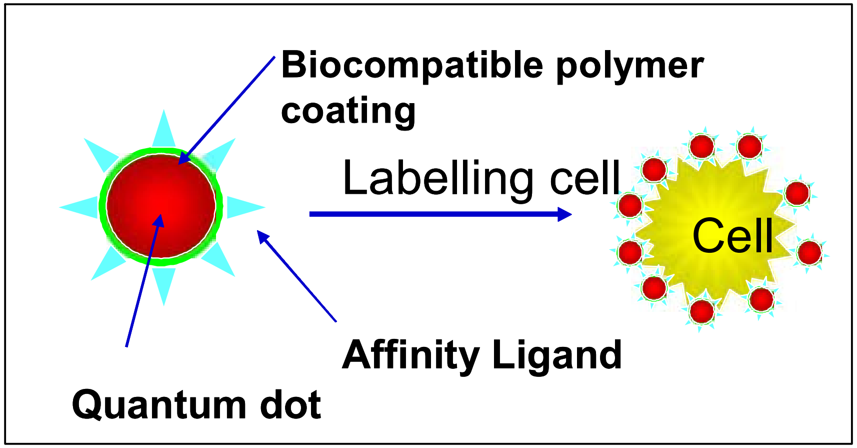
QD Biological Applications

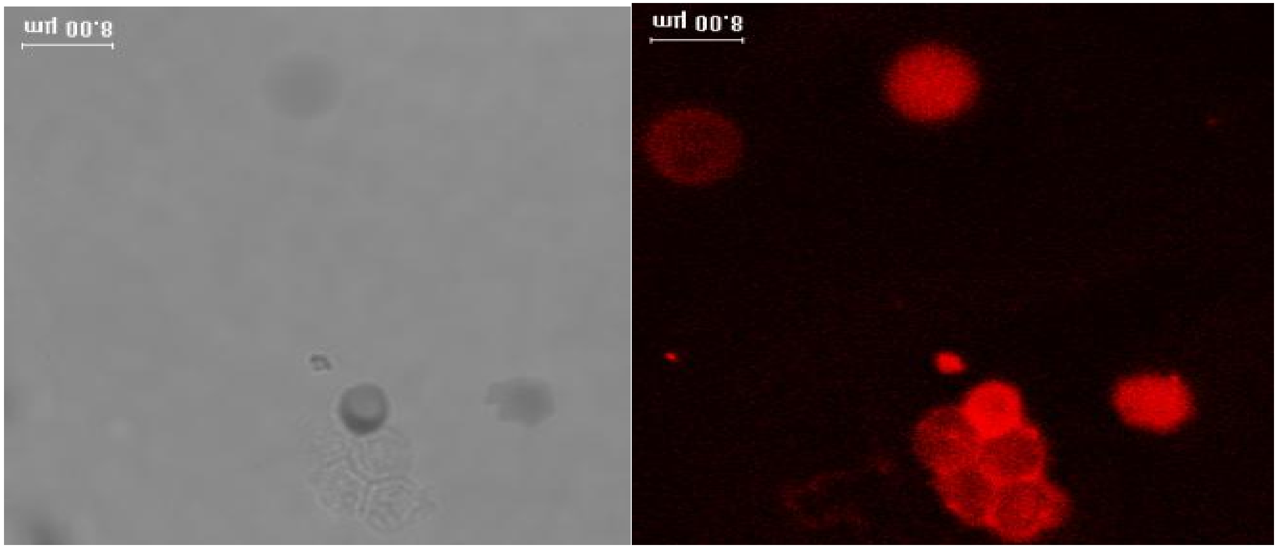






Healthcare and Life Sciences Luminescent component in biological probes



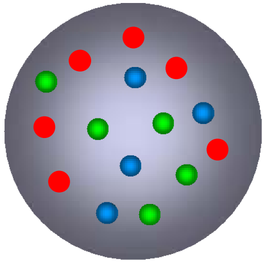


Confocal pictures of different size (A) 615nm,
(B) 489nmCdSe/ZnS QDs labeling Lymphocyte Cells

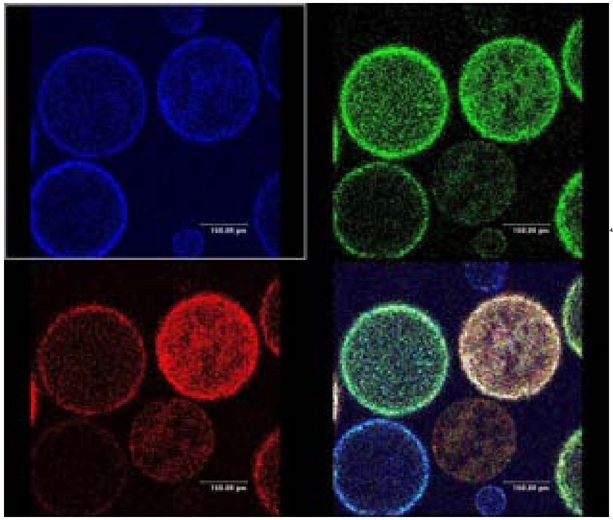
Quantum Dot Contain Beads

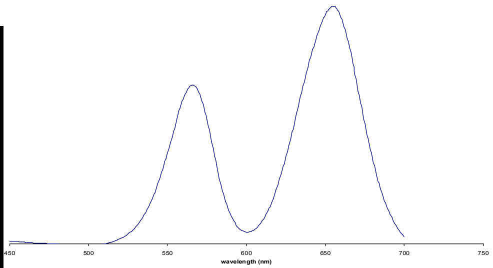
Quantum dot-containing polymer beads encoded beads

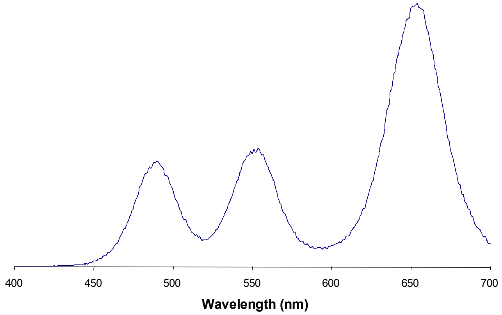
- High throughput screening
- Anti-counterfeiting
- Phosphors
- Monitoring flow systems

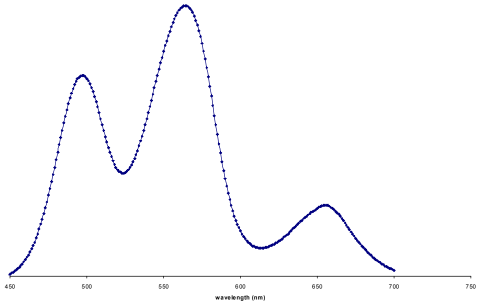


Schematic of a polymer bead containing three different colours of quantum dots to give an optical barcode





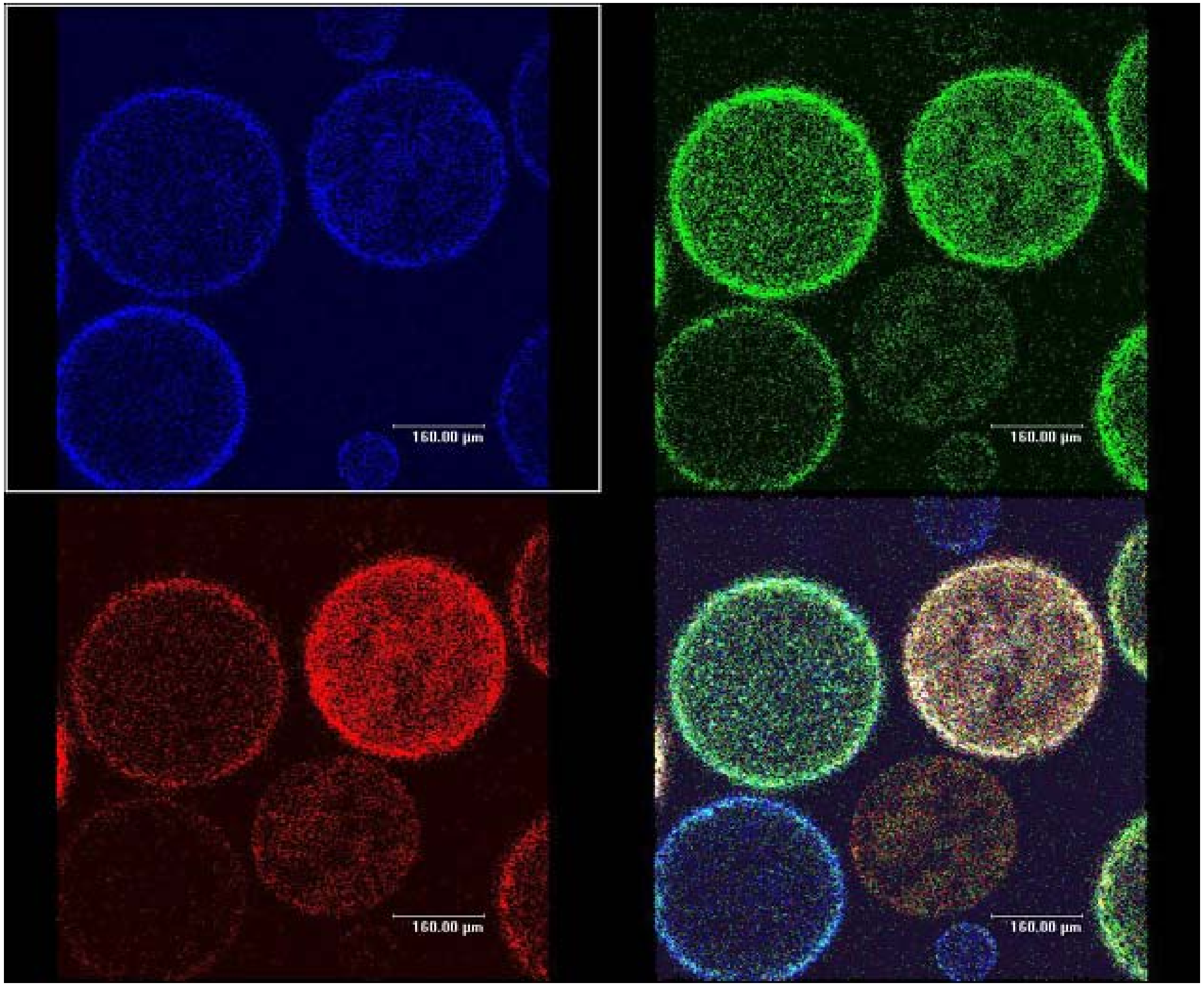




Nº of colours	Nº of intensities	Nº of combinations
2	2	4
3	3	27
4	4	256
5	5	3125

Microscope image of a polymer bead containing three different sizes of quantum dots and the photoluminescent emission spectrum of 3 different bead encodings

Identification of Beads by Fluorescence Profiles



4 types beads, 3 types QDs (532nm, 572nm & 628nm)

Chem. Commun, 2003, 2532 , J.Mater Chem., 2005,15,1238.

Summary

- World leading technology solution to existing problem – Scale up
- Nanoco is *de facto* partner of choice to QD application developers
- Large emerging market for QD based applications
- World leading technology and management team

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