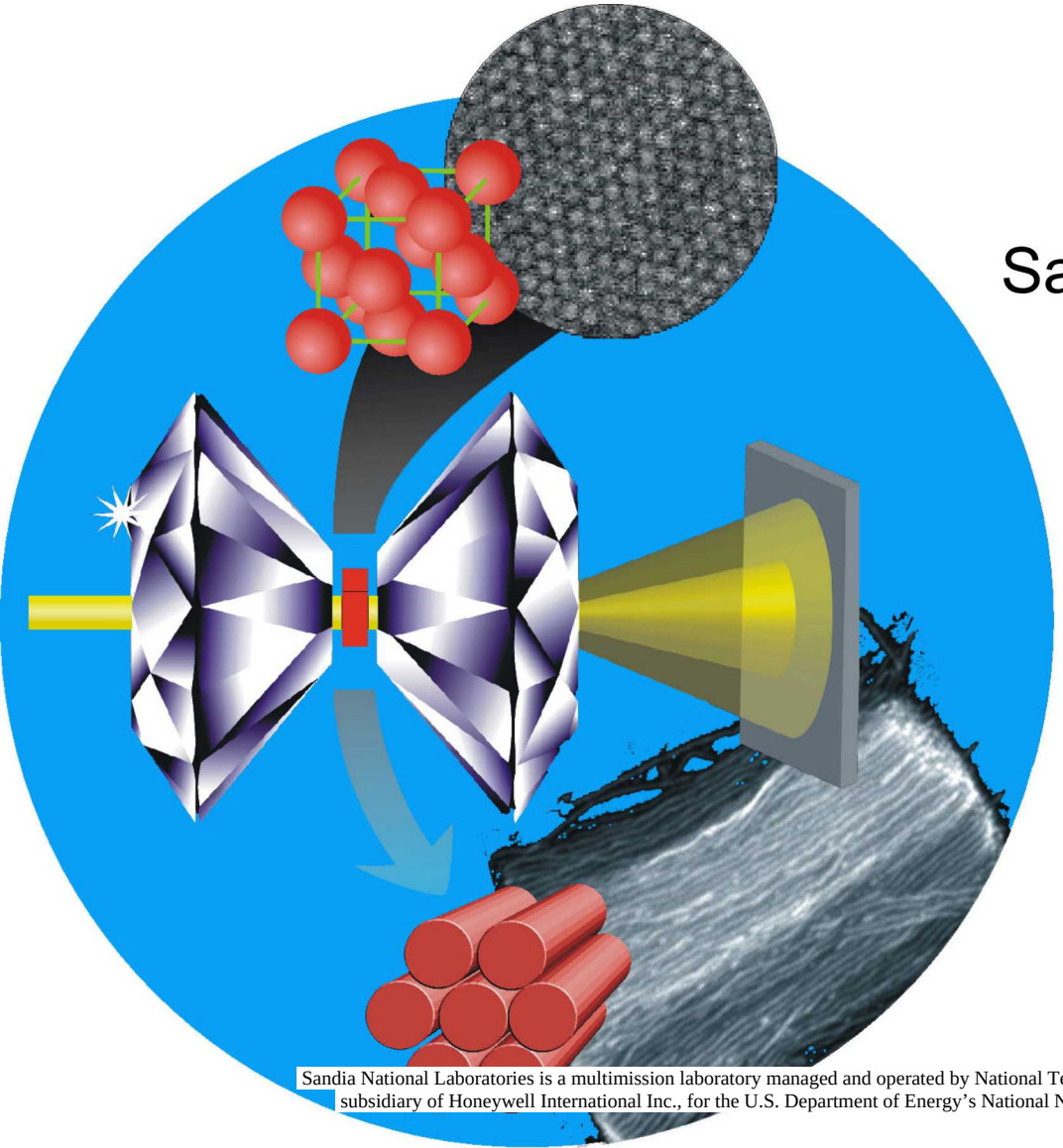
Stress induced mesoscale assembly of nanoparticles for active nanostructures

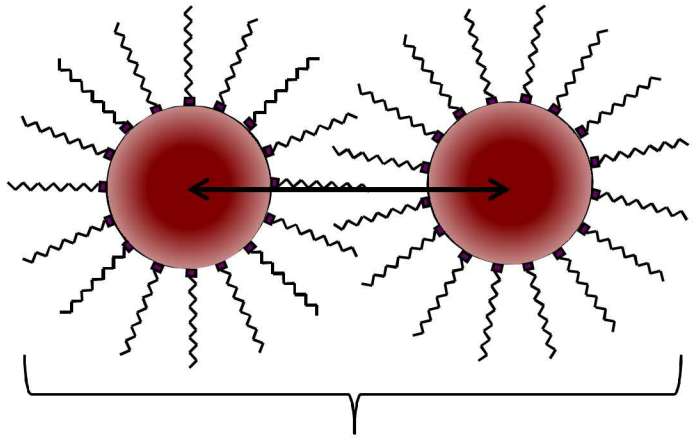
SAND2020-2446C



Hongyou Fan

Sandia National Laboratories

University of New Mexico



Nanoparticle interactions and coupling

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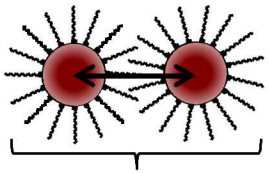
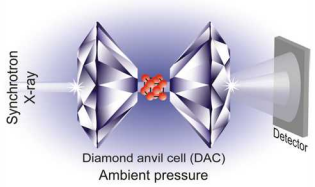
Outline

1. **Introduction - Nanoparticle Self-Assembly**



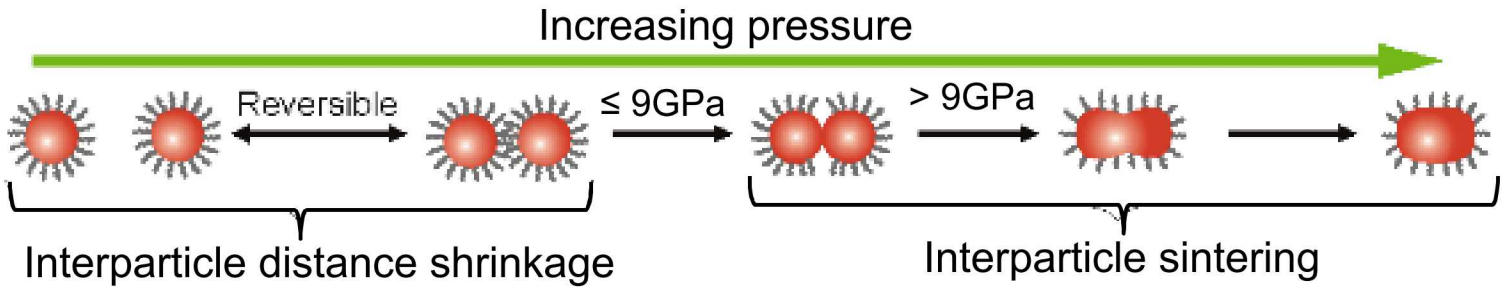
- Nanoparticle interactions
- Collective properties of nanoparticle arrays
- Current progress

2. **Pressure-Induced Assembly and Formation of 1-3D Nanostructures**

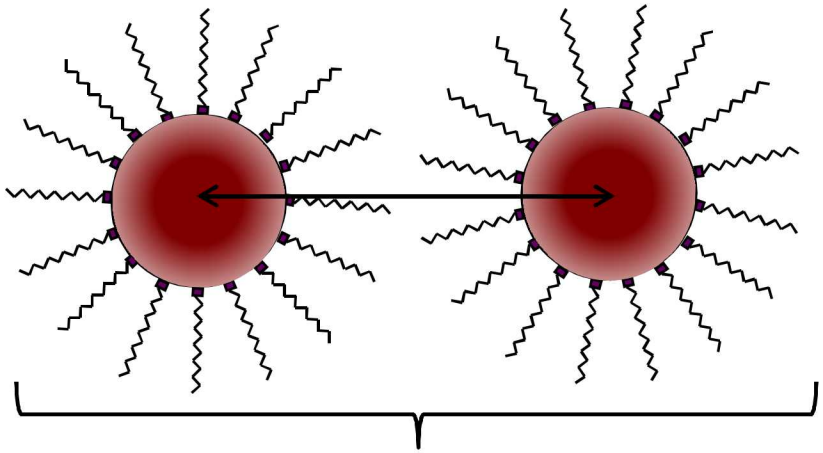


- High pressure induced assembly
- 1-3D metallic nanostructures (Au and Ag)
- Semiconductor nanowires (CdSe, etc.)
- Pressure-tuned nanoparticle coupling and collective property

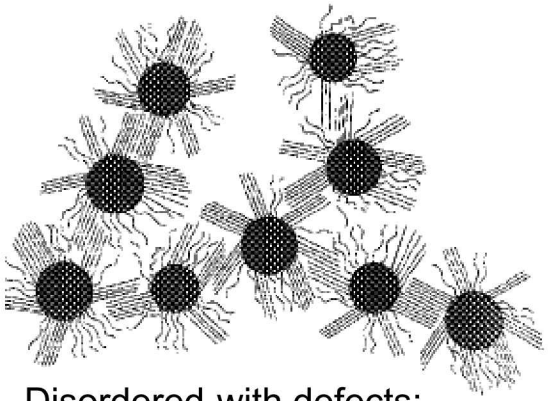
3. **Summary**



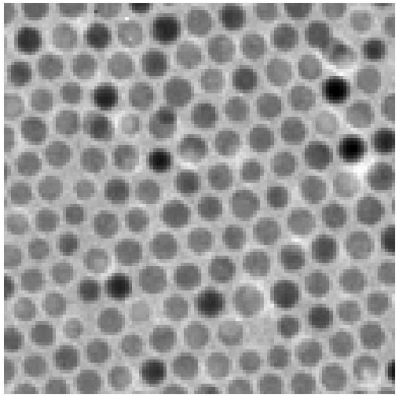
Nanoparticle Assembly at Ambient Pressure: Balanced Nanoparticle Interactions



Balanced Nanoparticle interactions:
- Attraction
- Van der Waals
- Charge interactions
- Dipole-dipole
- …



Disordered with defects: vacancy, grain boundary, etc.

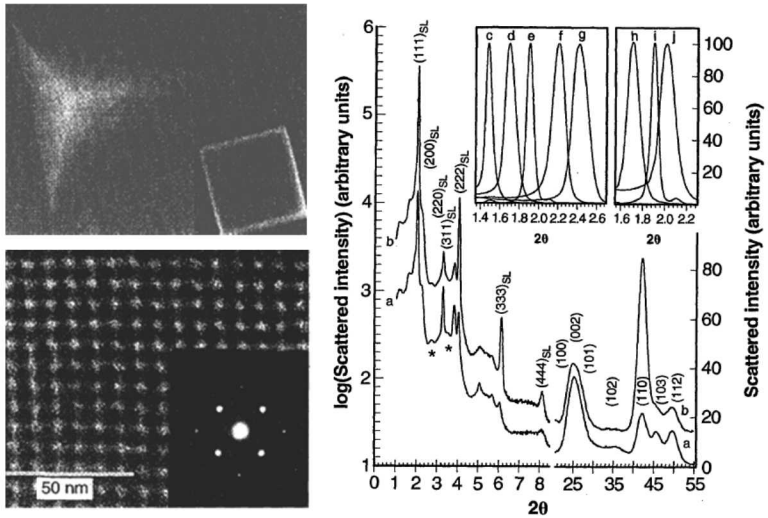


Ordered array

Lennox, R.B. *et al. Chem. Eur. J.* vol. 2, 359-363, 1996,

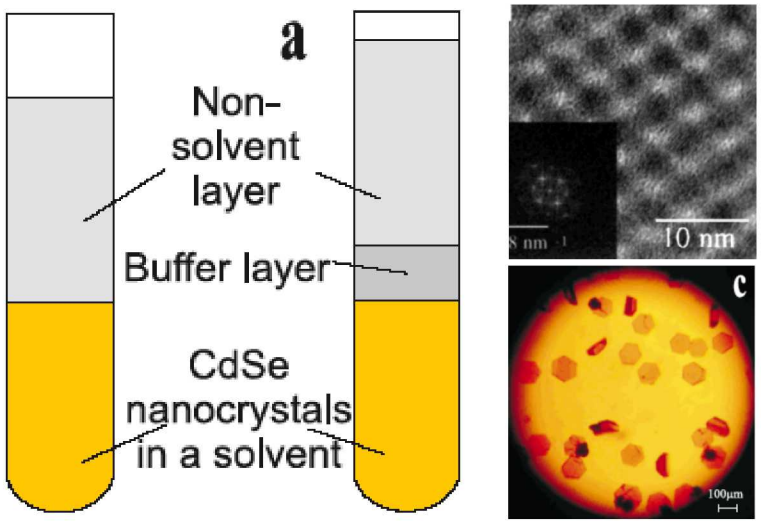
Nanoparticle Self-Assembly at Ambient Pressure: 1. Balanced Nanoparticle Interactions

1. Solvent anealing



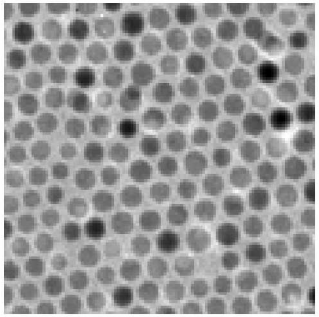
Murray, et al., *Science*, 1995.

2. Heterogeneous nucleation



Talapin, et al., *Adv. Mater*. 2001.

3. Solvent Evaporation



Ordered thin film

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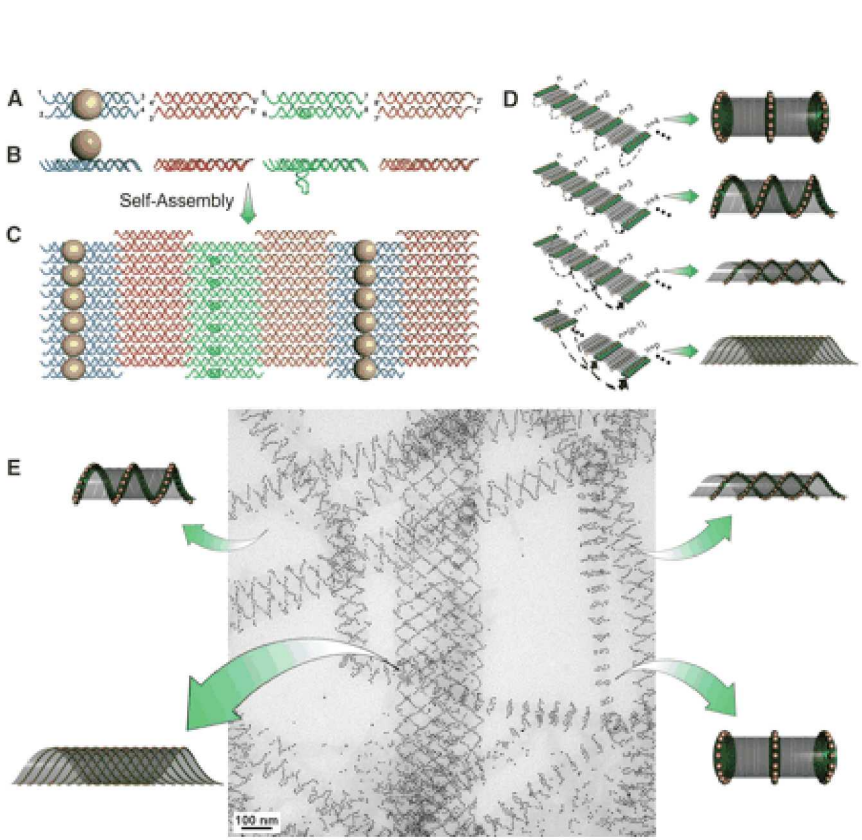
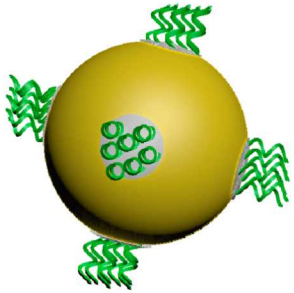
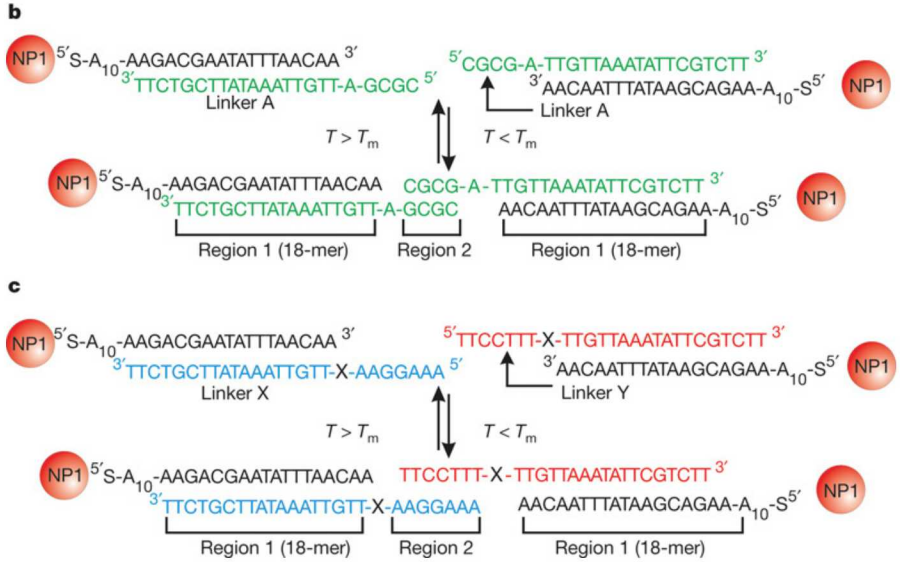
Nanoparticle Self-Assembly at Ambient Pressure: 2. DNA-Programmable Nanoparticles

Ligand-receptor interactions







Y. Li, et al. JACS, 2015, 137, pp4320-4323; Jaswinder Sharma, *et al.*, *Science* 323, 112-116, 2009; Sung Yong Park, *et al.*, *Nature* 451, 530-556, 2008; Dmytro Nykypanchk, *et al.*, *Nature* 451, 549, 2008.

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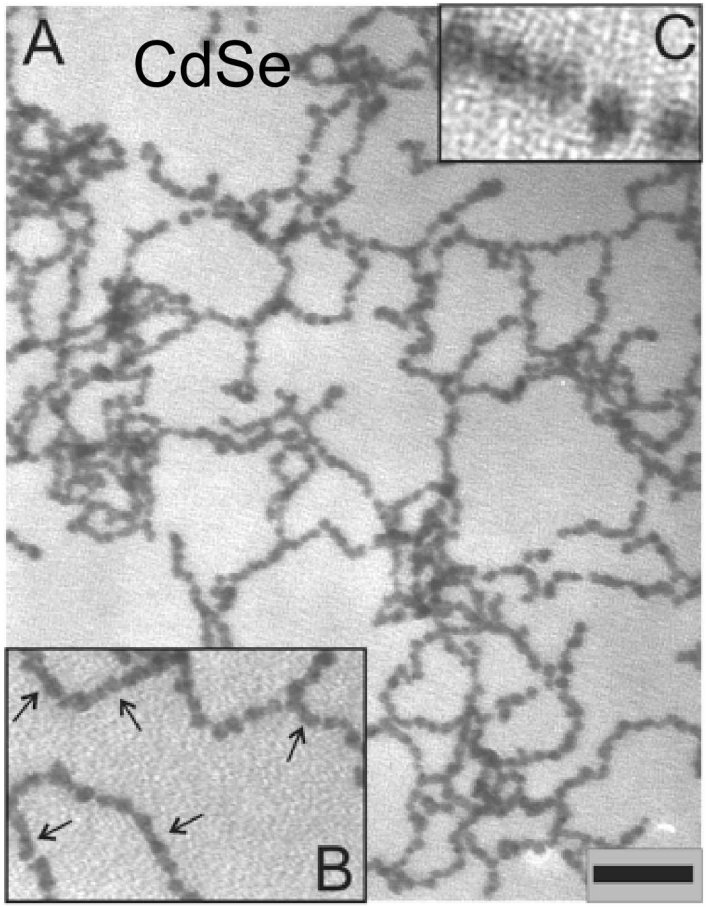
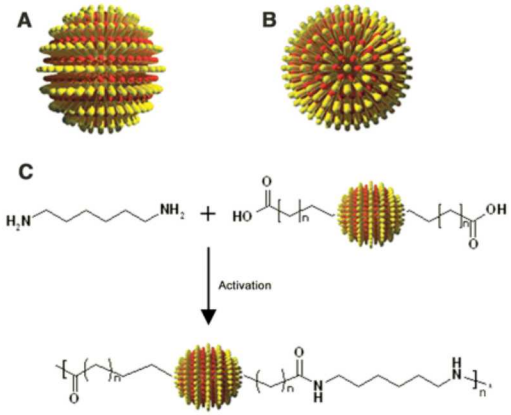
Nanoparticle Self-Assembly at Ambient Pressure: 3. Dipole-Dipole Interactions and Chemical Reactions

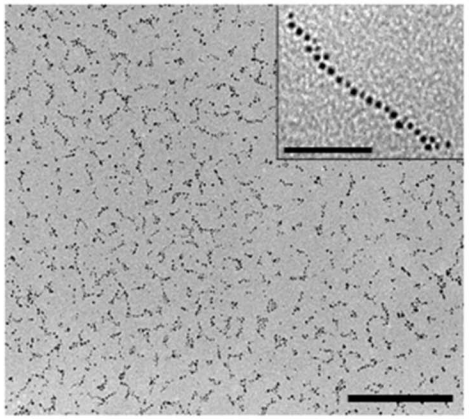
Dipole-Dipole Interaction



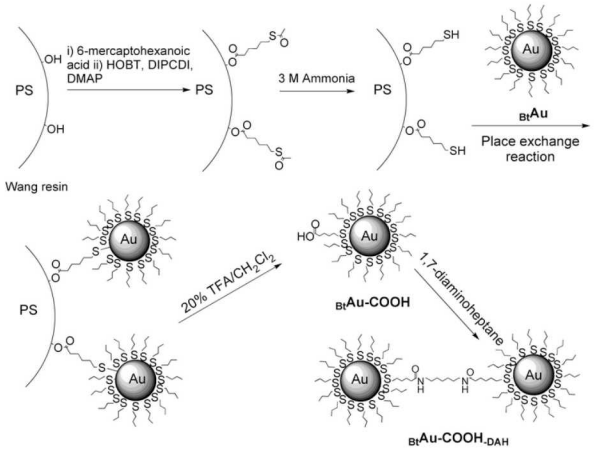
Z. Y. Tang, *et al., Science* 297, 237, 2002.

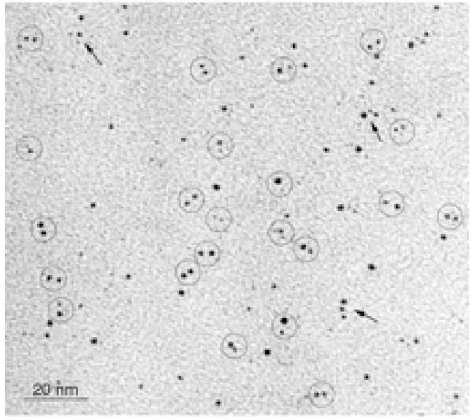
Chemical Reactions





G. A. DeVries, *et al., Science* 315, 358, 2007.





J. G. Worden, *et al., Chem. Comm.*, 518, 2004.

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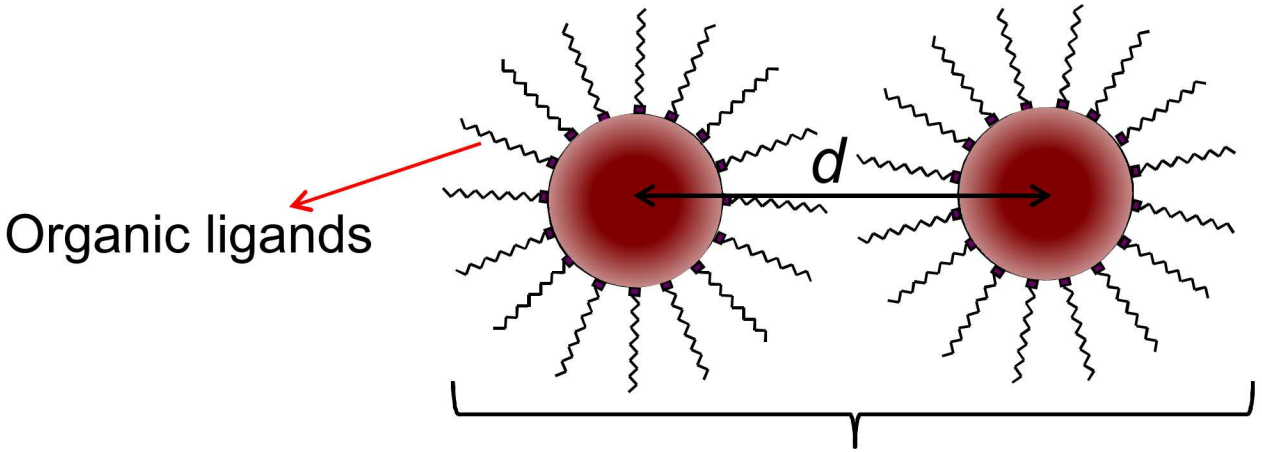
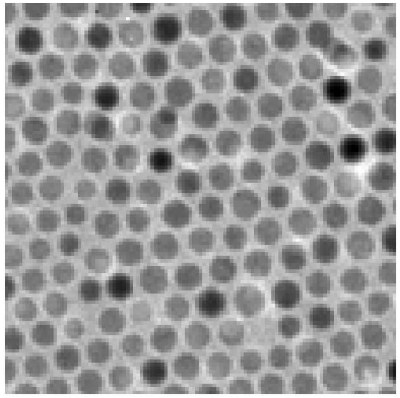
Nanoparticle Interactions and Coupling

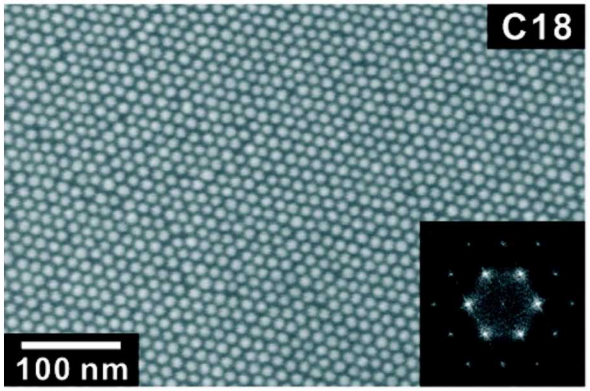
Nanoparticle coupling depends on interparticle separation distance

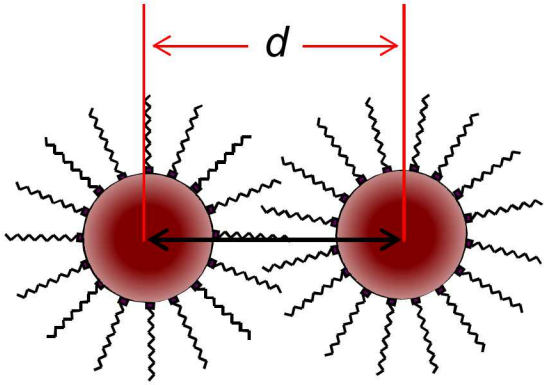


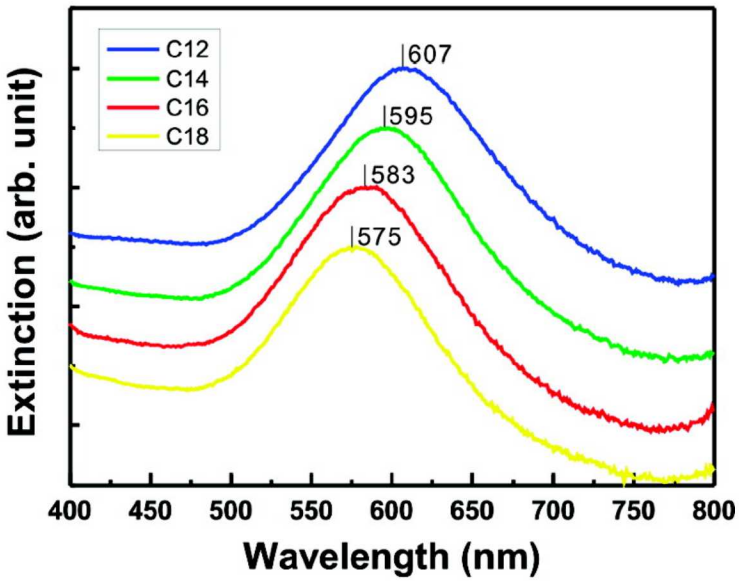


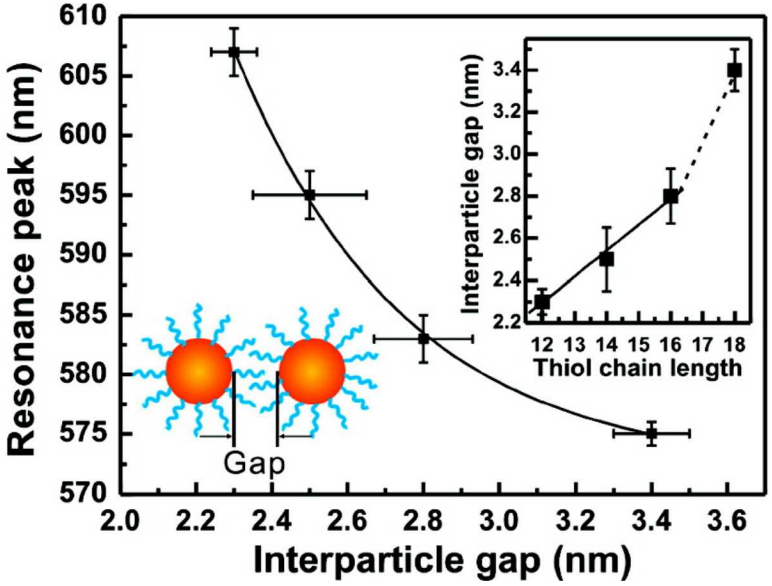
Balanced nanoparticle interactions:
- Attraction
- Van der Waals
- Charge interactions
- Dipole-dipole
- …

Tuning Plasmonic Response from Alkanethiolate-Stabilized Gold Nanoparticle Superlattices









Chi-Fan Chen, *et al.*, *J. Am. Chem. Soc.,* 130, 824-826, 2008.

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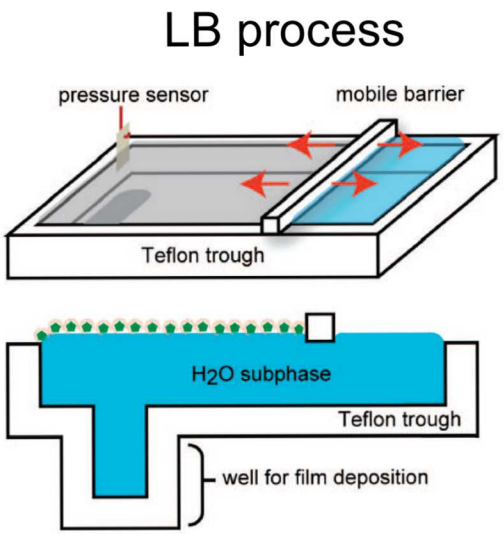
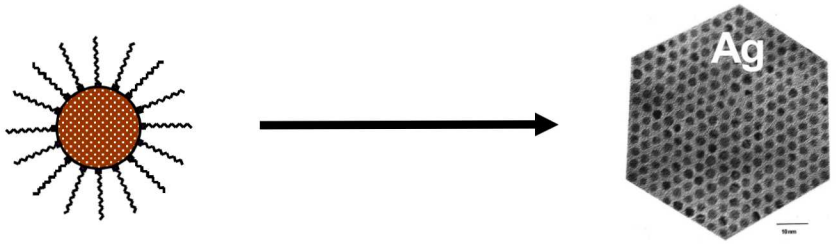
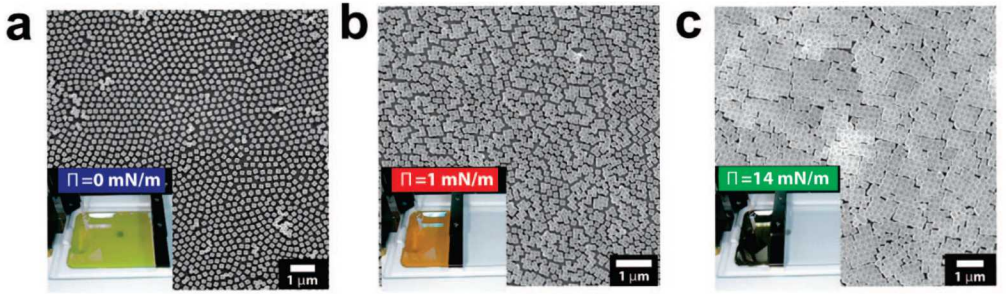
Langmuir-Blodget to Tune Nanoparticle Separaion

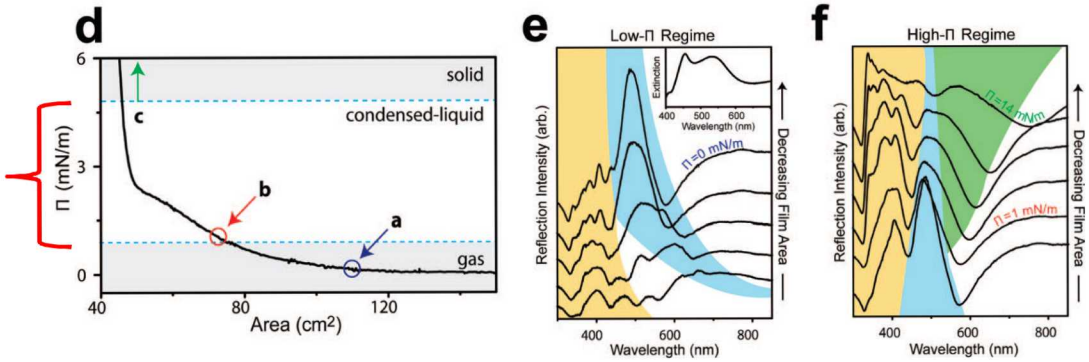




C. P. Collier, *et al*, *Science*, 227, 1978-1981, 1997.



- uniaxial pressure
- 2-dimensional
- limited pressure range



Tao, A. R. *et al.*, *Acc. Chem. Res.*, vol. 41, No. 12, 1662-1673, 2008.

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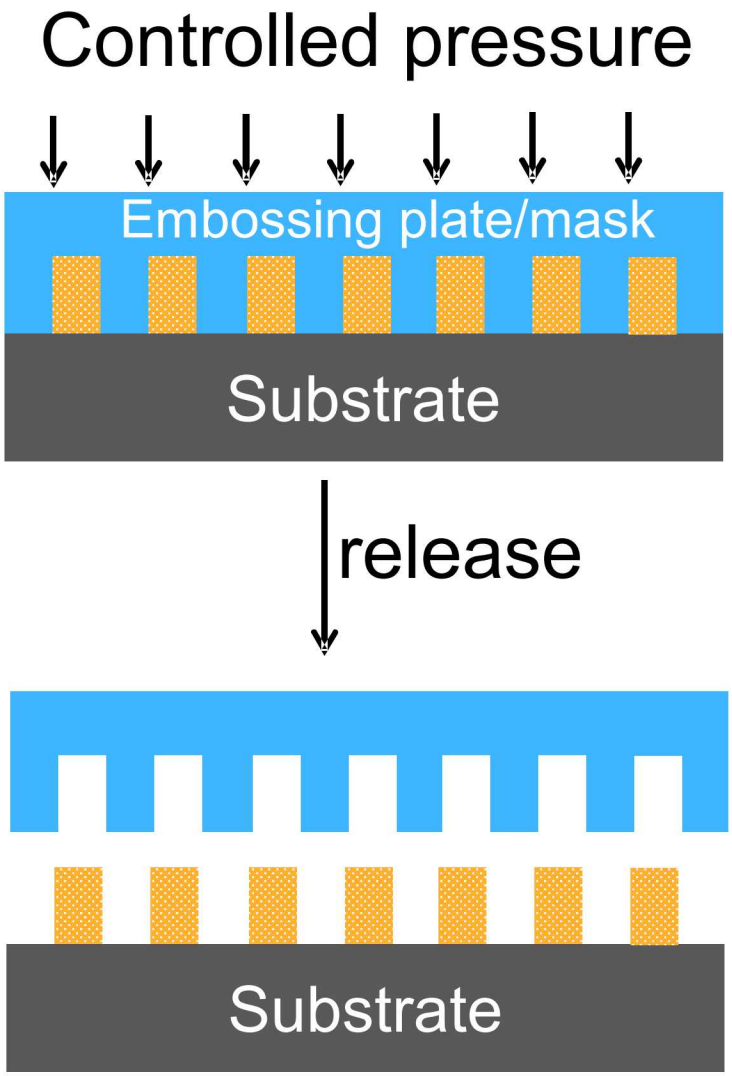
Our Research – Pressure Induced Nanoparticle Assembly:
Mimic Manufacturing Processes - Embossing or Imprinting



Features:

- Rapid
- Cost effective
- High throughput
- High fidelity

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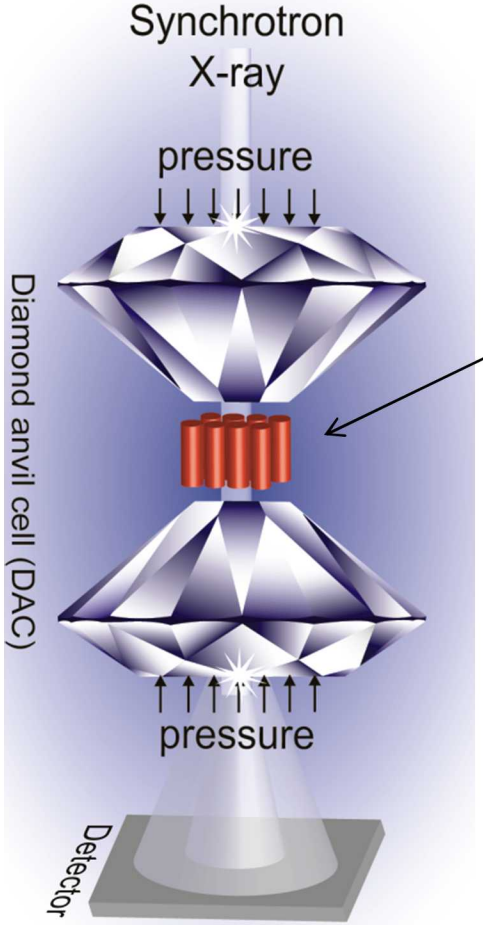
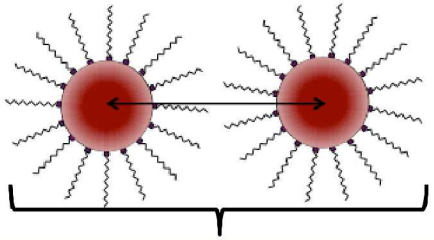
Pressure-Induced Assembly and Fabrication

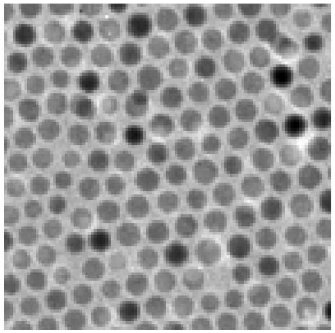
An external pressure overcomes balanced interparticle interactions, enables engineering of nanoparticle assembly, allowing fine-tuning of lattice structure and interparticle separation distance to fabricate new nanoparticle architectures.



Diamond Anvil Cell (DAC)



Balanced Nanoparticle interactions:
- Attraction
- Van der Waals
- Charge interactions
- Dipole-dipole
- …



- Provide controlled pressure fields:
  - Hydrostatic & uniaxial
  - Controlled pressure range
- Allow in-situ structural and property characterizations
  - Absorption, emission, etc.
  - Crystal structure, phase transition, etc.
  - Structural evolution with pressure

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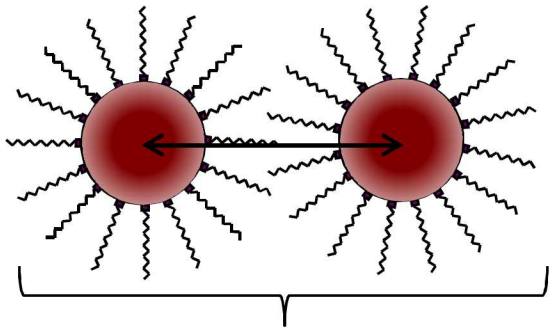
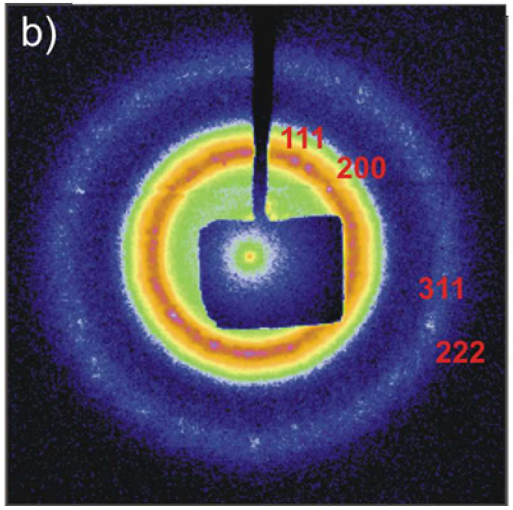
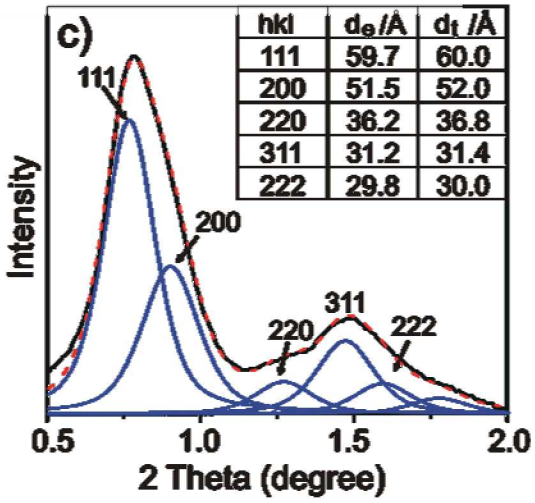
Before Compression – Starting Materials: Ordered Spherical Gold Nanoparticle Arrays



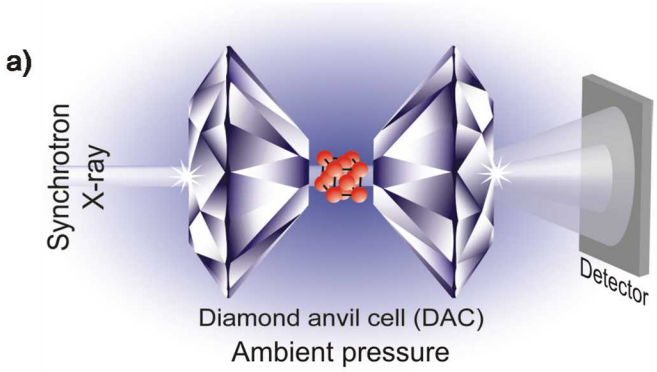
Balanced particle interactions

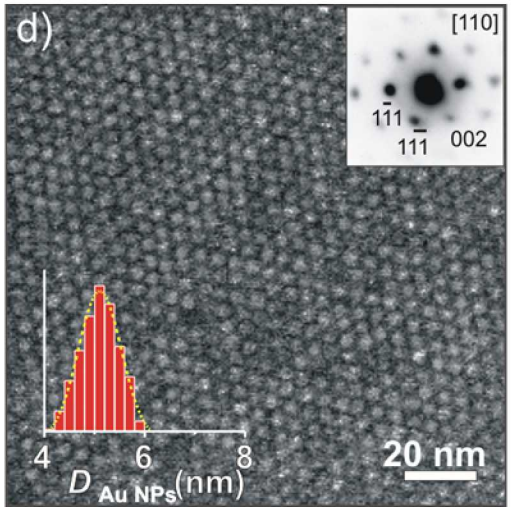
5 nm gold nanoparticles and *fcc* lattice (a = 10.4 nm)

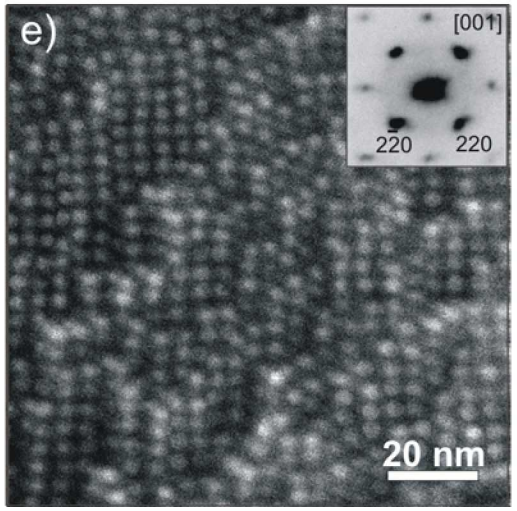




hkl	d_e /Å	d_t /Å
111	59.7	60.0
200	51.5	52.0
220	36.2	36.8
311	31.2	31.4
222	29.8	30.0







Wu H., Fan H., *et al. Angew. Chem. Int. Ed.,* 49, 8431-8434, 2010.

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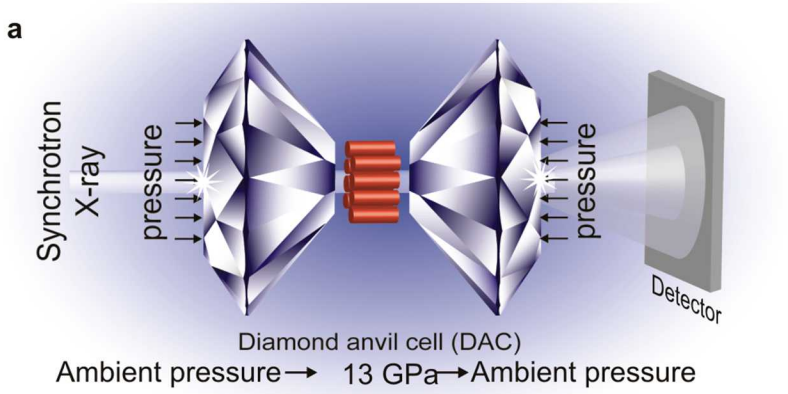
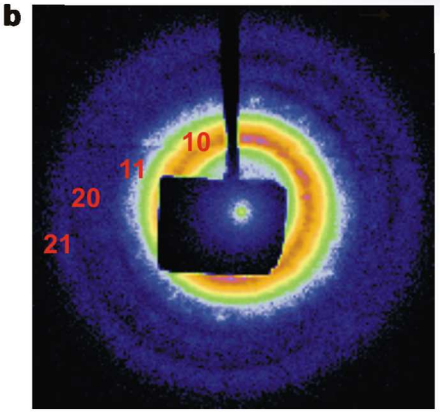
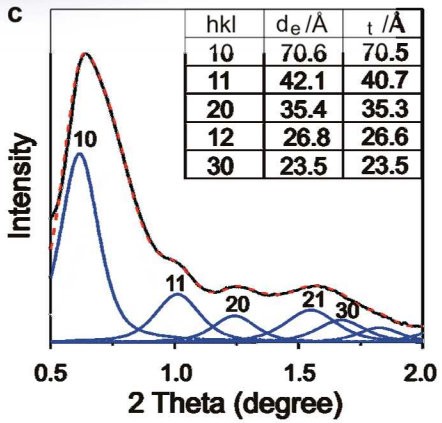
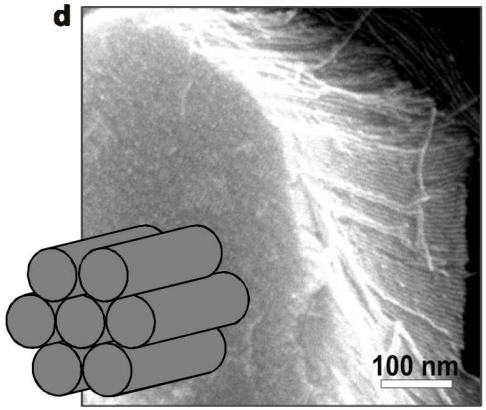
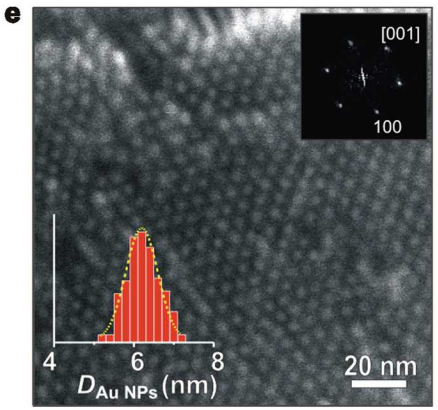
After Compression – Formation of 1D Nanowires

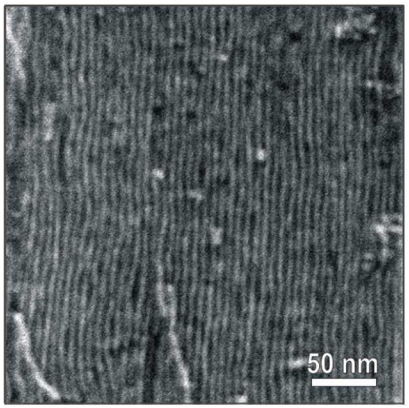


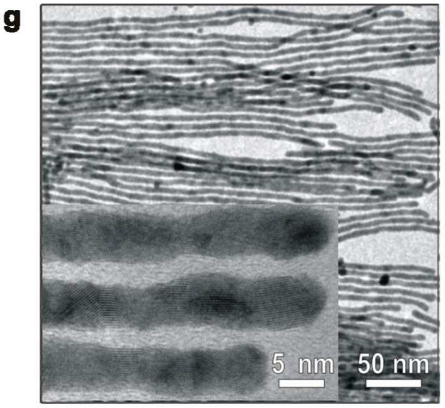












Wu H., Fan H., *et al. Angew. Chem. Int. Ed.,* 49, 8431-8434, 2010.

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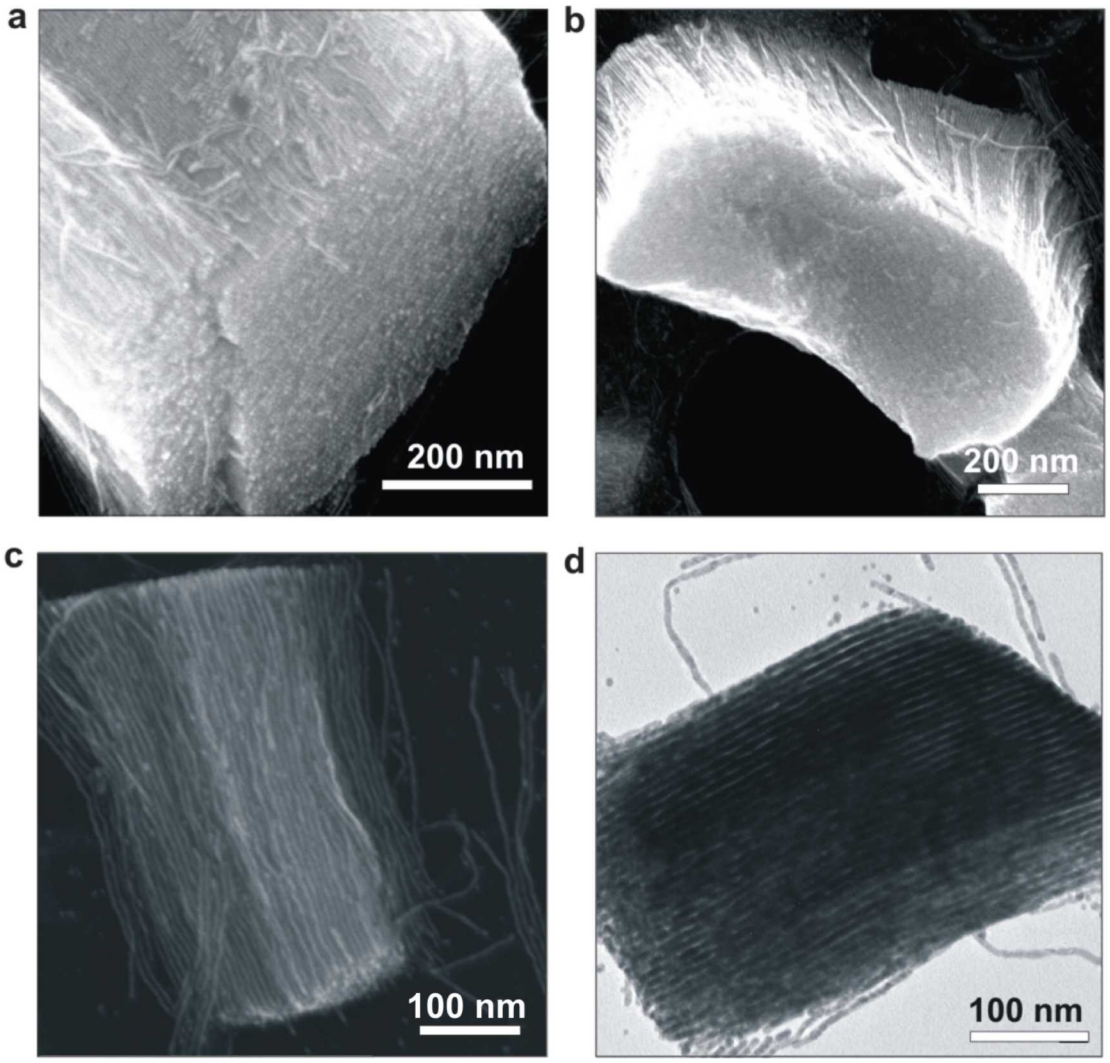
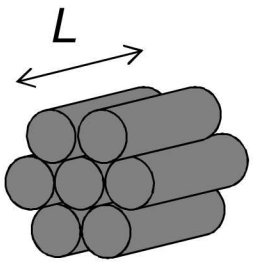
Bundles of 1D Nanowire Arrays

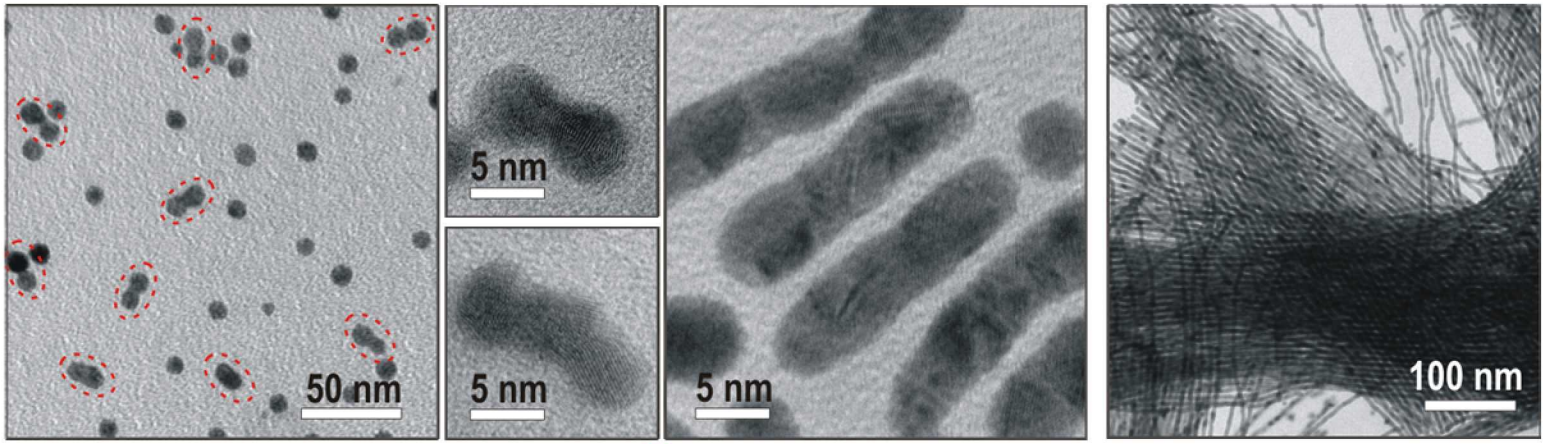


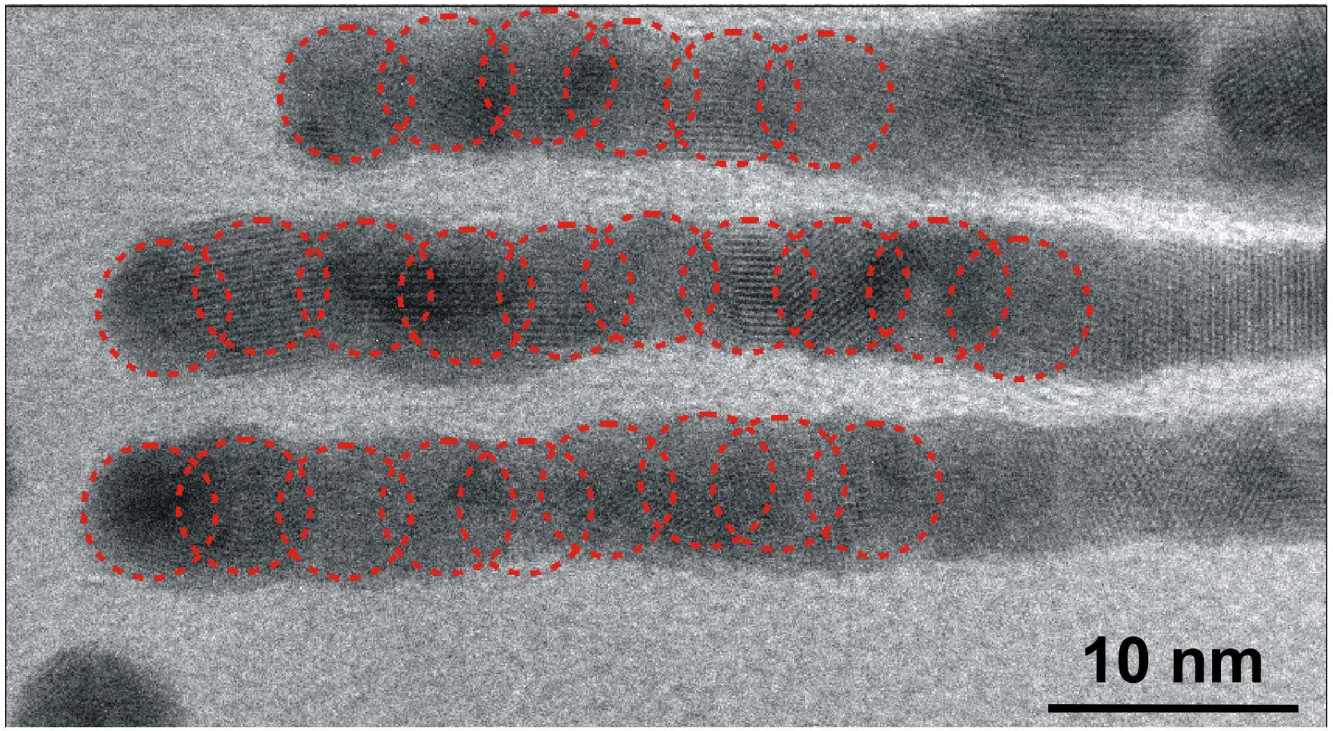
Uniform length



Wu H., Fan H., *et al. Angew. Chem. Int. Ed.,* 49, 8431-8434, 2010.

Pressure Tuned 1D Nanostructures





Diameter
~ 5 nm

Wu H., *et al. Angew. Chem. Int. Ed.,* 49, 8431-8434, 2010.

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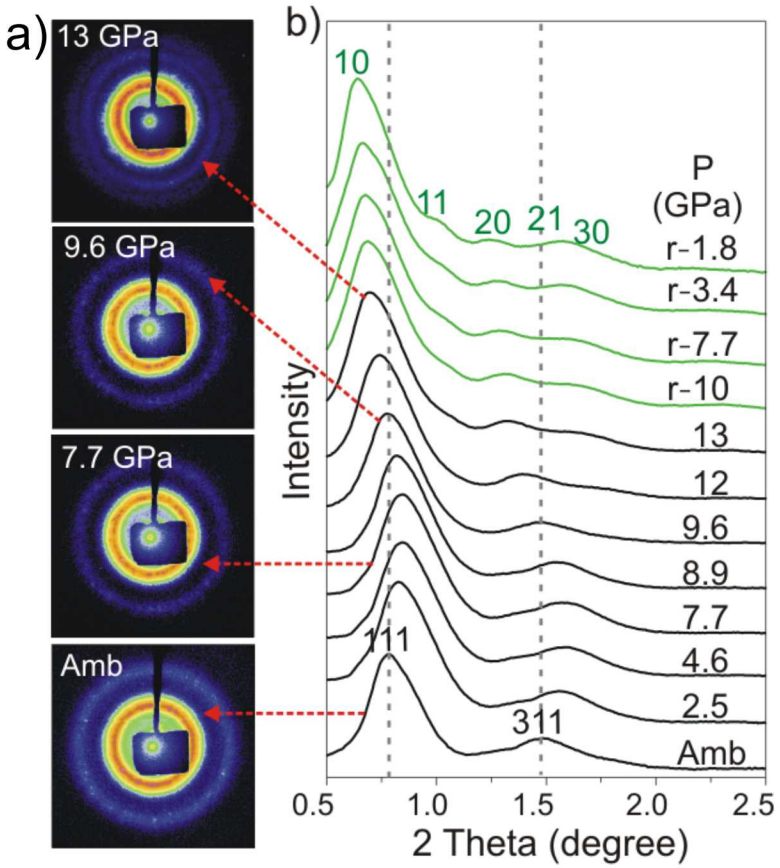
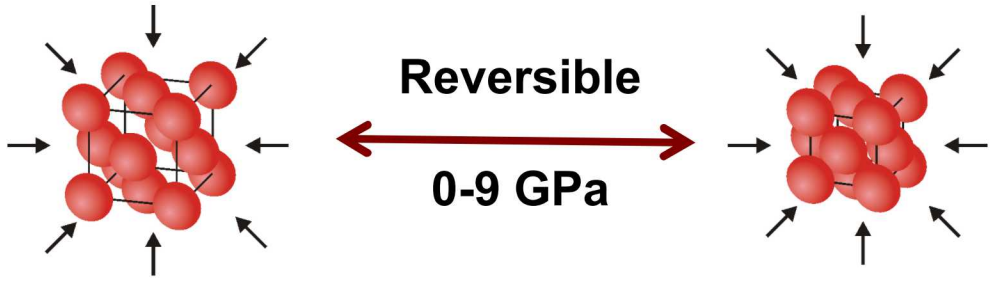
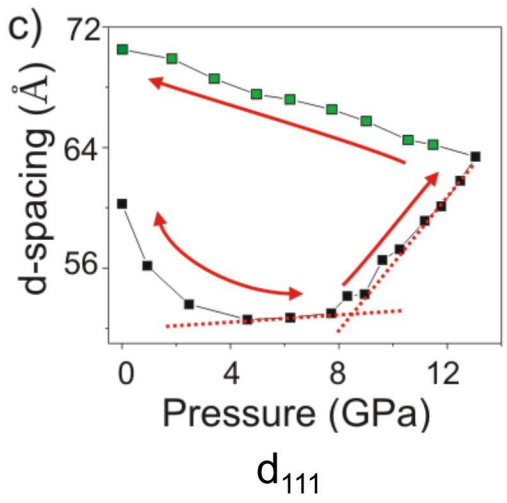
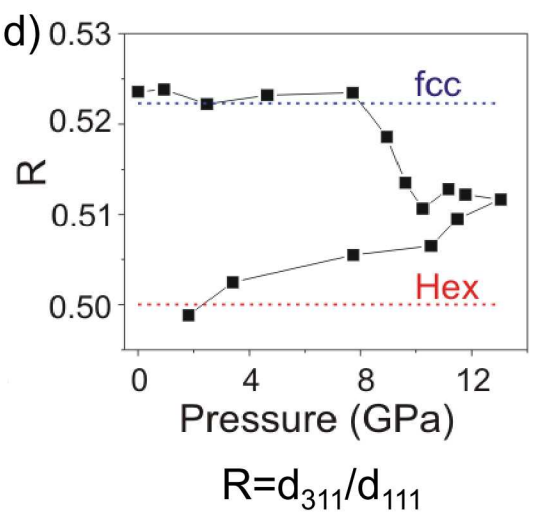
In-situ Synchrotron X-ray Studies of Nanoparticle Assembly under Pressure

An external pressure overcomes specific interparticle interactions, enables engineering of nanoparticle assembly, allowing fine-tuning of lattice structure and interparticle separation distance to fabricate new nanoparticle architectures.









Wu H. & Fan H. *et al.*, *J. Am. Chem. Soc.*, 132, 12826-12828, 2010
& *Angew. Chem. Int. Ed.*, 49, 8431-8434, 2010.

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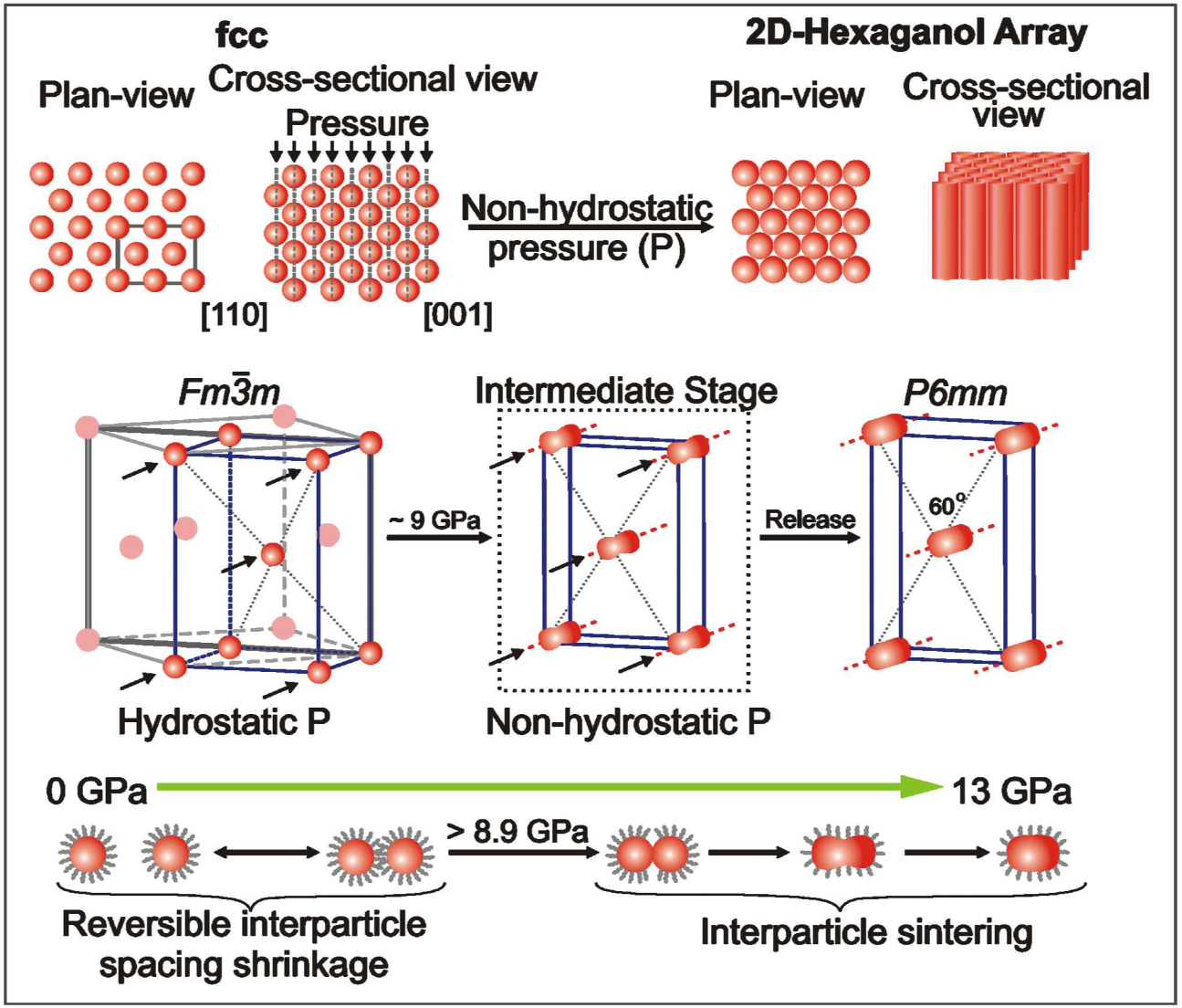
Pressure-Induced Nanoparticle Assembly Processes



Wu & Fan *et al.*, *J. Am. Chem. Soc.*, 132, 12826-12828, 2010 & *Angew. Chem. Int. Ed.*, 49, 8431-8434, 2010.

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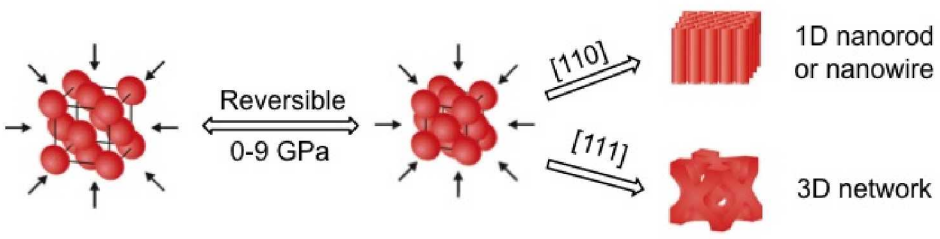
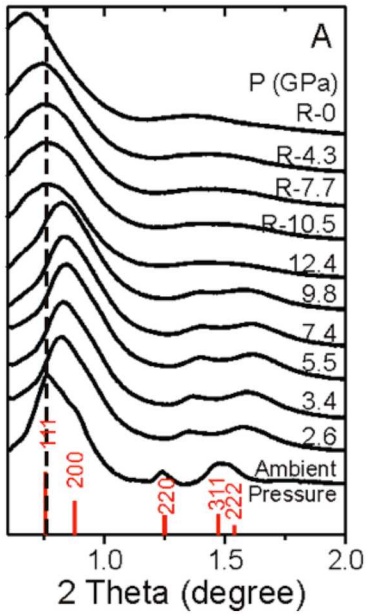
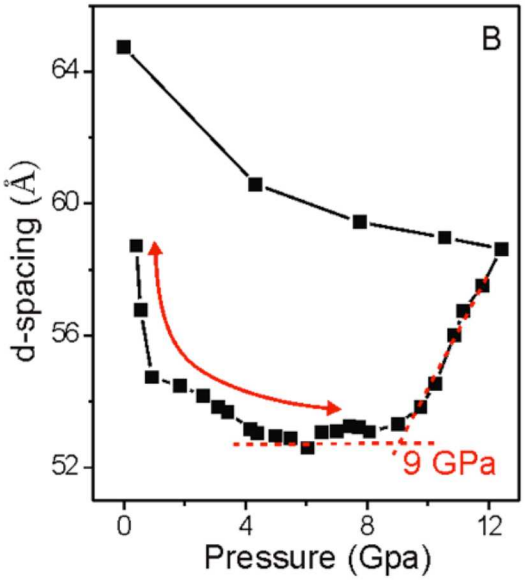
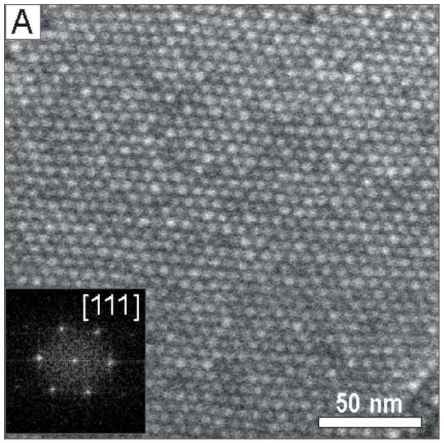
Pressure-Induced Formation of 3D Nanostructures

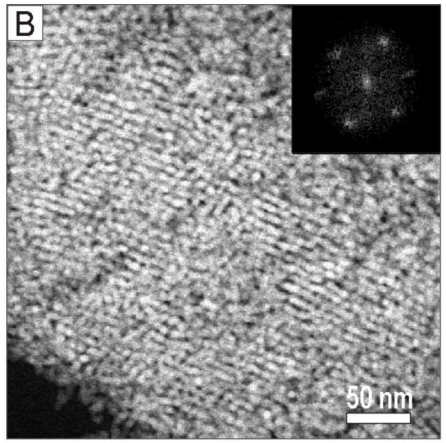
Interconnected 3D gold networks are formed depending on initial nanoparticle packing

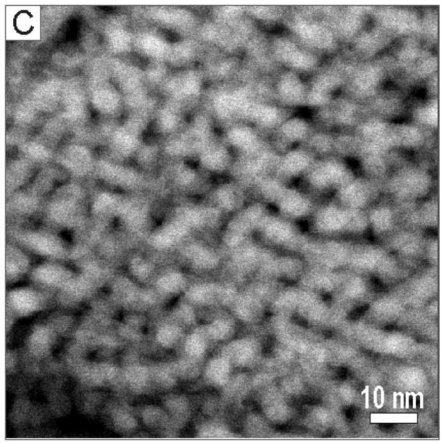


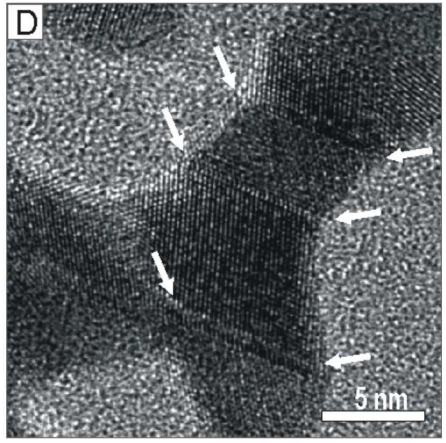












Wu H., Fan, H. *et al*., *J. Am. Chem. Soc*., 132, 12826, 2010 & *J. Am. Chem. Soc. 136*, pp 7634, 2014.

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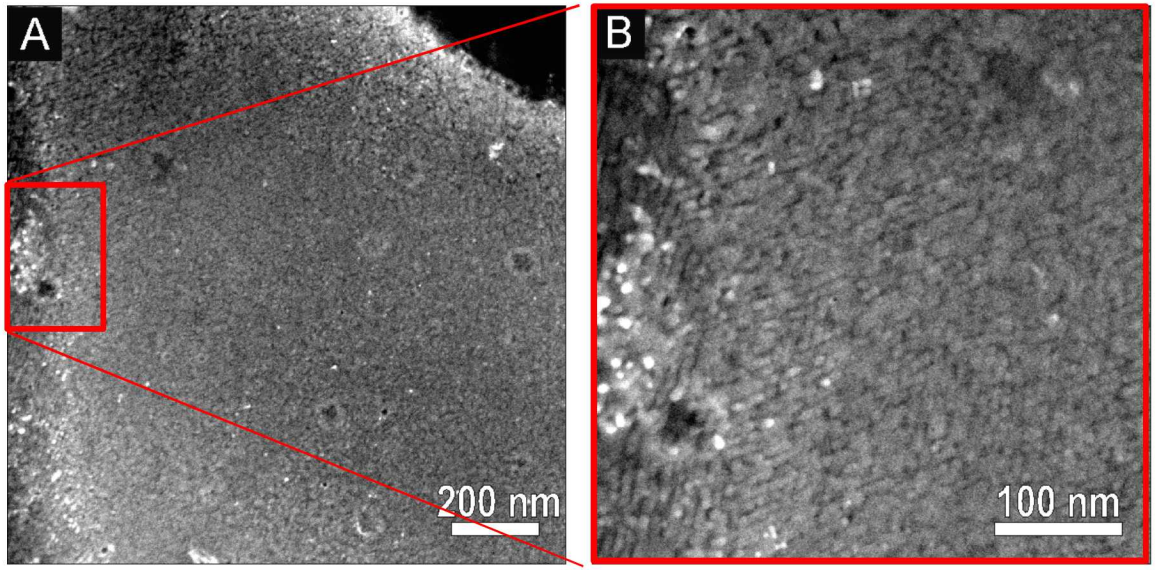
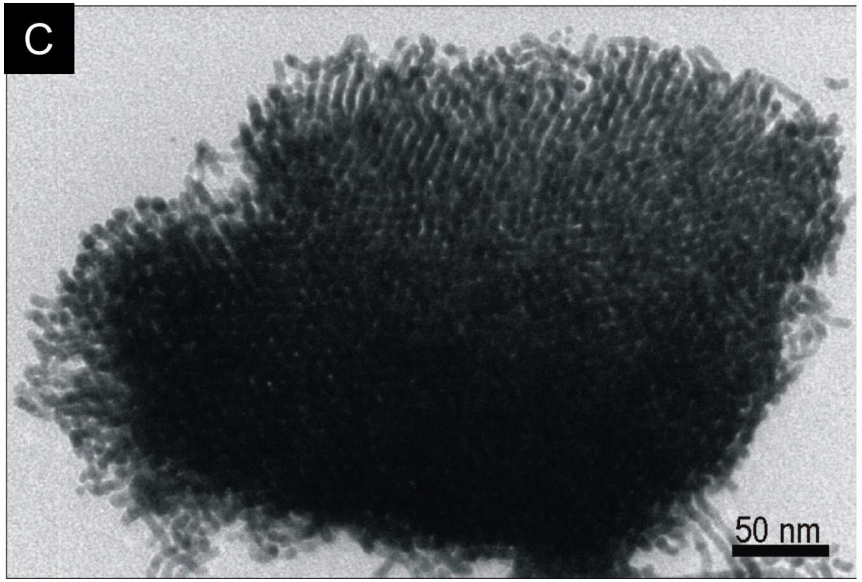
Electron Microscopy of 3D Networks

SEM images



TEM image



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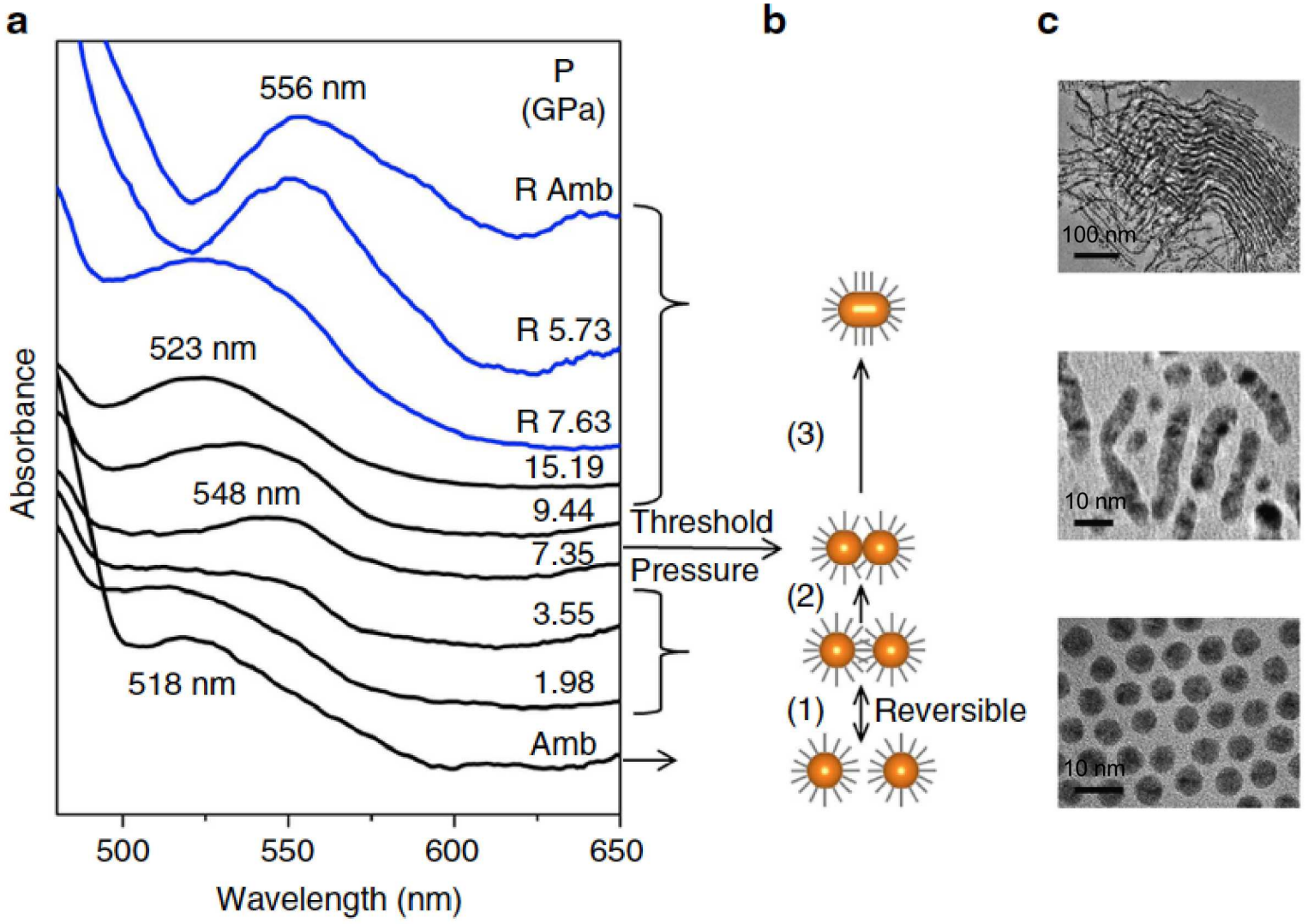
Wu, H. et al. *J. Am. Chem. Soc.* 2014, 136, 7634−7636.

Pressure-Tuned Nanoparticle Interactions and Coupling

Structure - optical property correlation of Ag nanoparticle arrays



Adv. Mater. 2016, 28, 1989–1993.

Li, B.; Fan H., *et al*., *Nat.Commun.* 5:4179 doi: 10.1038/ncomms5179 (2014).

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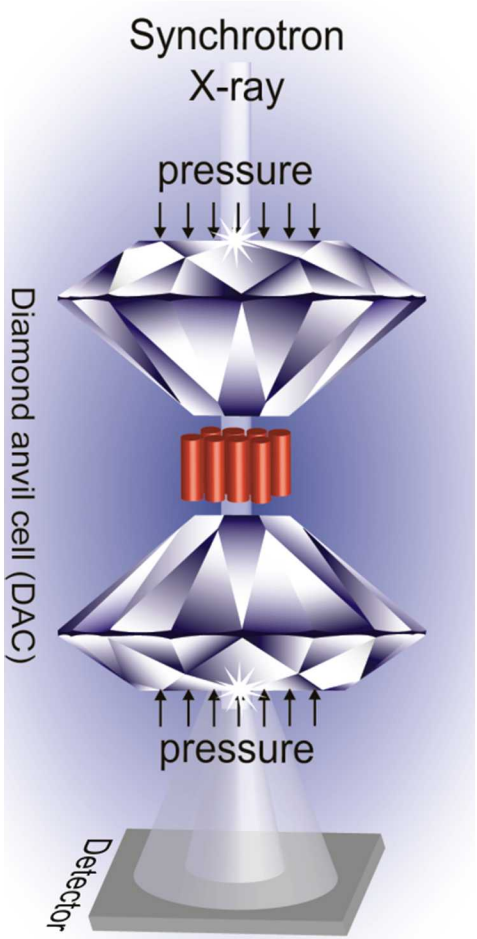
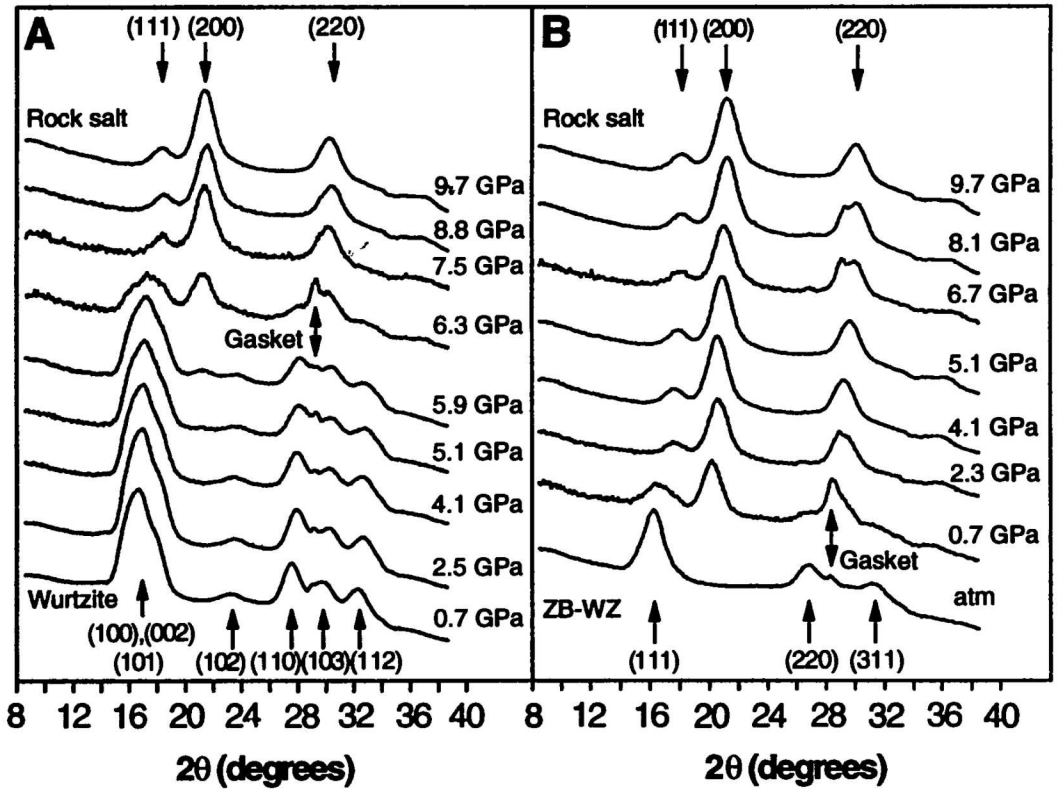
Semiconductor Nanoparticles (CdSe) under Pressure

Previous studies were focused on structural transformation in atomic lattice of CdSe nanoparticles and associated optical property changes under pressure.



Wurtzite → Rock salt → Zinc Blende



Tolbert S.H., Alivisatos A.P., *Science,* 265: 373-376, 1994 &
J. Chem. Phys. 102: 4642-56, 1995.

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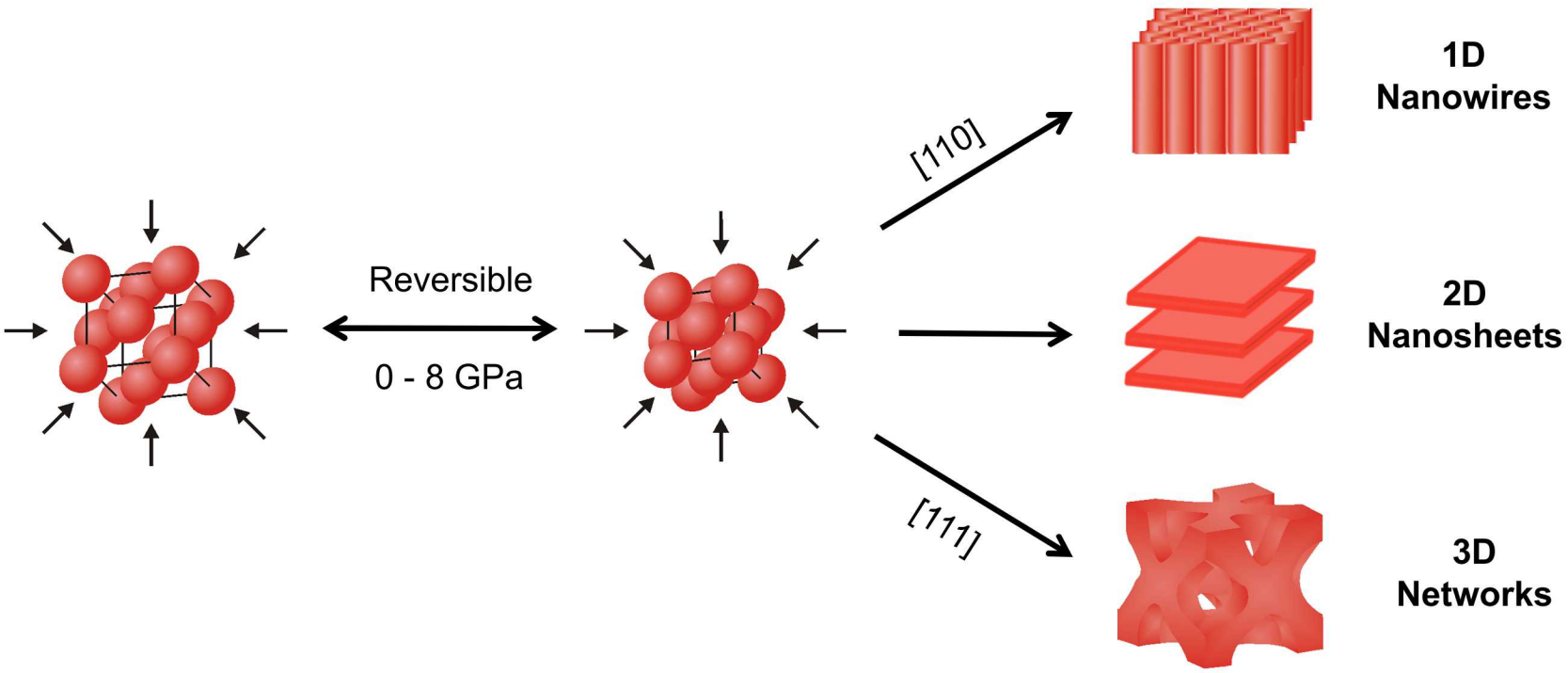
Semiconductor Nanoparticles (CdSe) under Pressure

Our studies were focused on structural transformation in CdSe nanoparticle mesophase and fabrication of new nanostructures under pressure.



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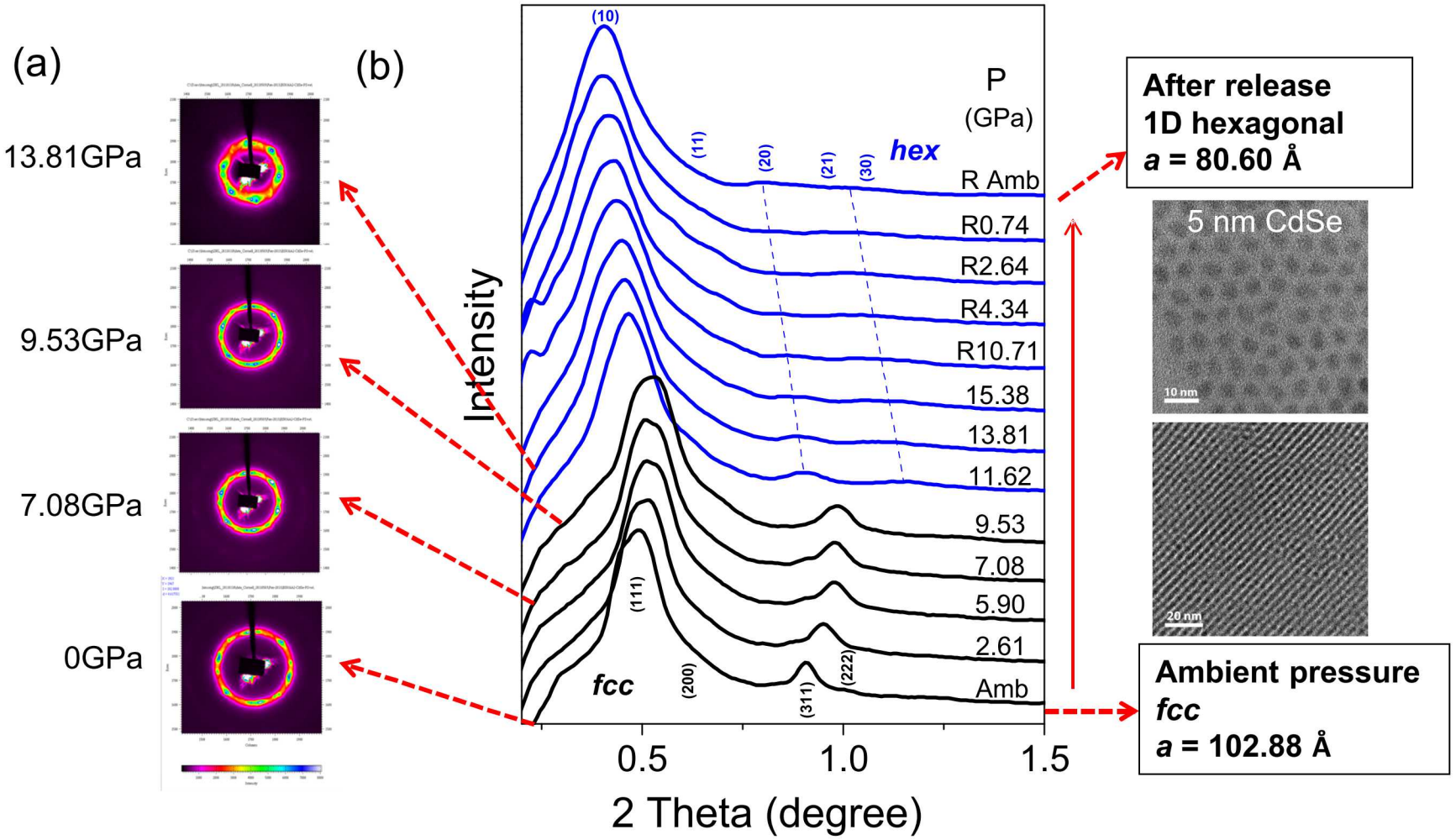
Li, B. et al. *Nat. Commun.* 8, 14778 doi: 10.1038/ncomms14778 (2017).

Structural Evolution of Ordered, Self-assembled CdSe Nanoparticle Arrays under Pressure

5 nm CdSe nanoparticles coated with Octadecylphosphonic acid (ODPA), Trioctylphosphonic oxide (TOPO)



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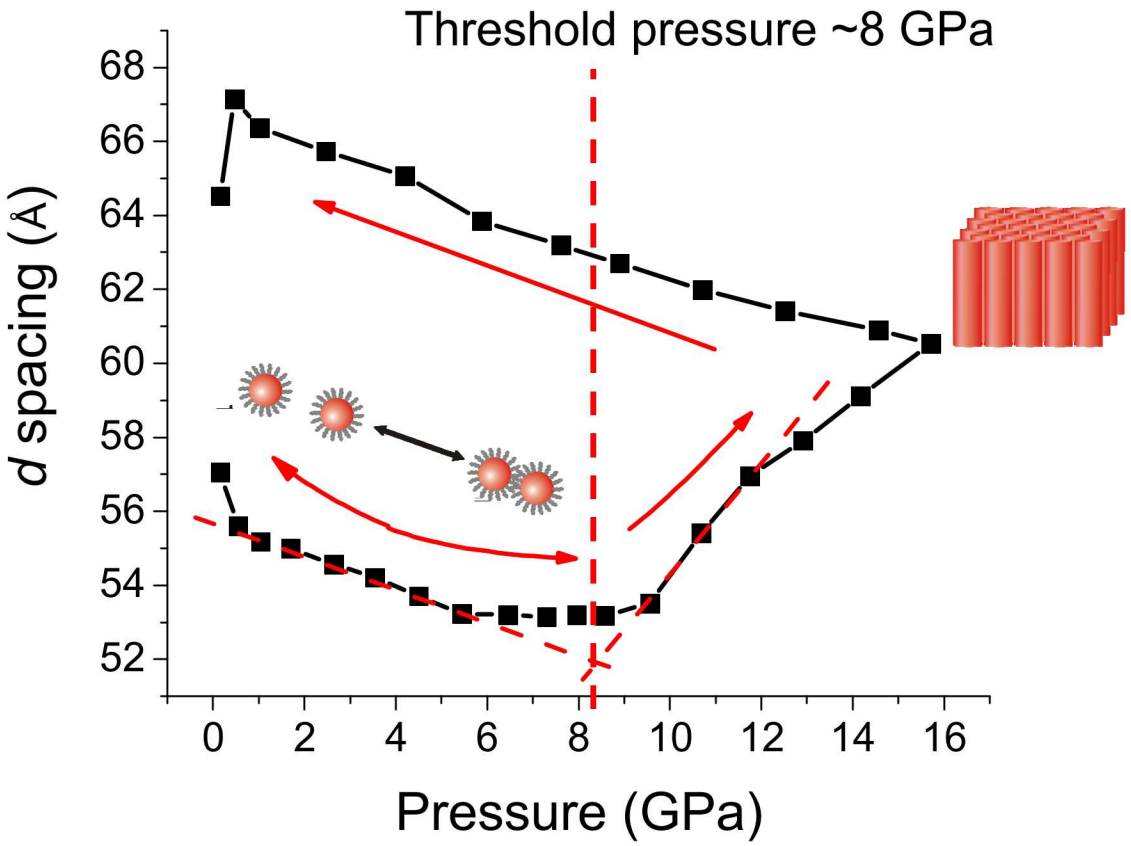
B. Li, K. Bian, et al, *Science Advances* 3, e1602916 (2017).

Tunable Interparticle Spacing in CdSe Arrays during Compression and Release



Graph shows the *d*-spacing of the first Bragg reflection in each HP-SAXS spectrum.

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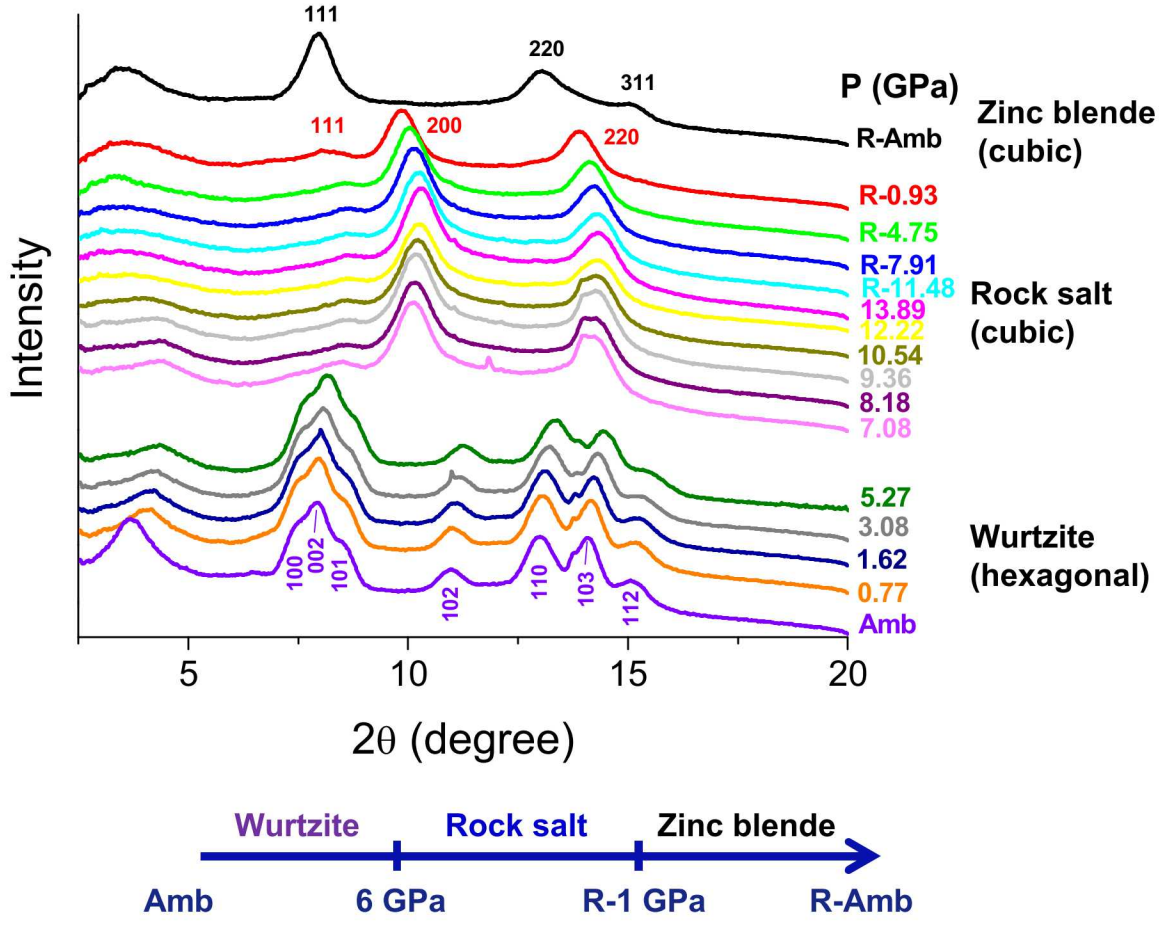
B. Li, K. Bian, et al, *Science Advances* 3, e1602916 (2017).

Atomic Lattice Phase Transition of CdSe Nanoparticles during Compression and Release



B. Li, K. Bian, et al, *Science Advances* 3, e1602916 (2017).

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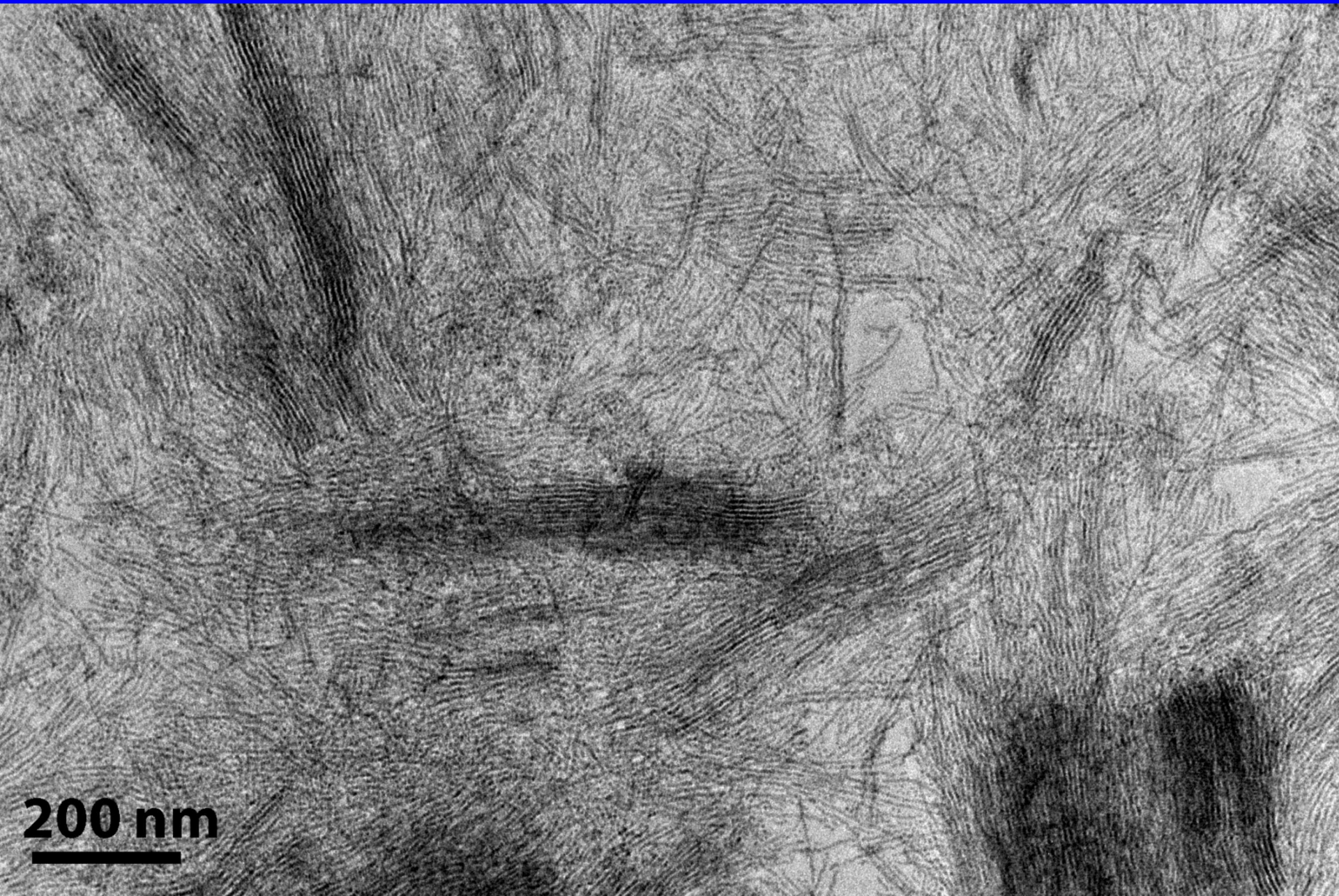
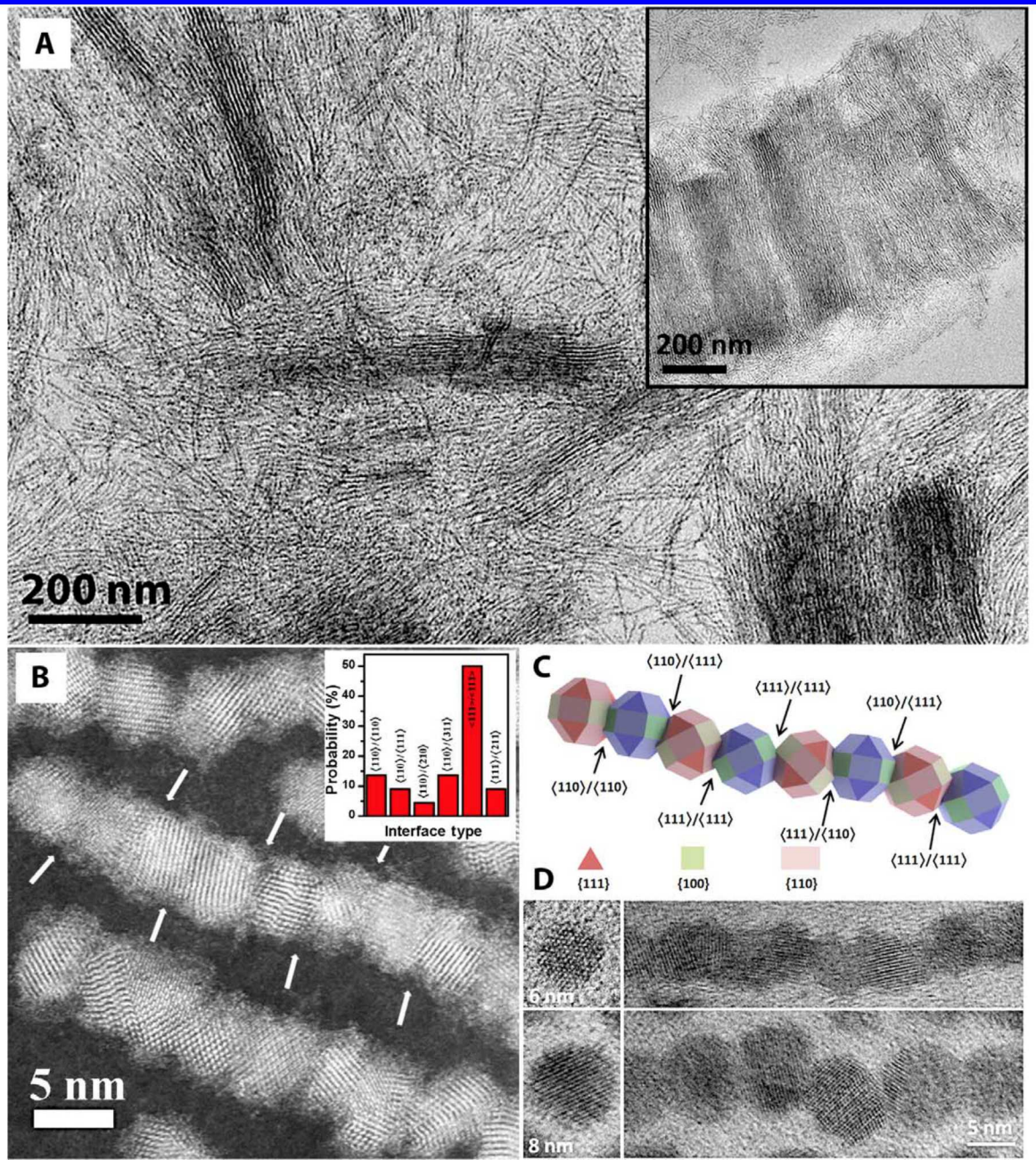
Transmission Electron Microscopy Image of CdSe Nanowires



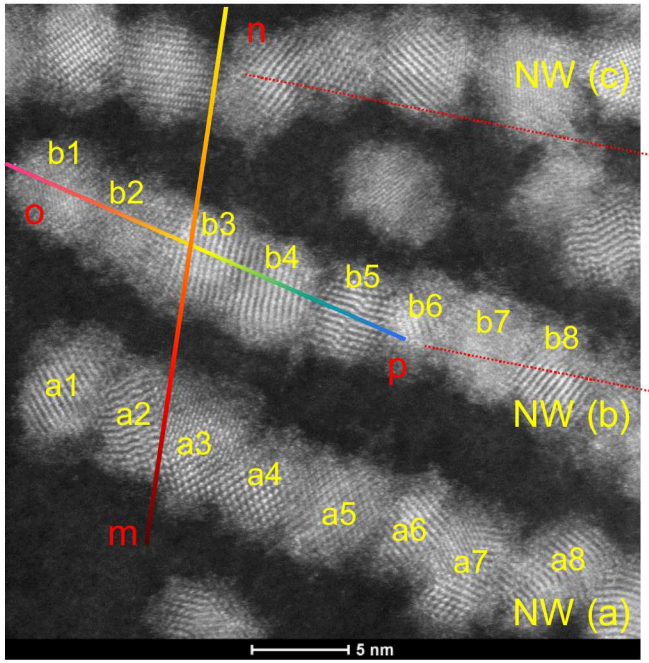
Transmission Electron Microscopy Image of CdSe Nanowires



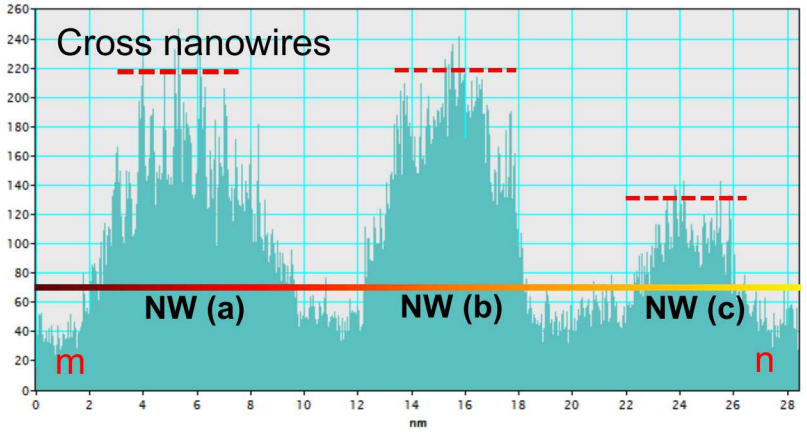
B. Li, K. Bian, et al,
Science Advances
3, e1602916 (2017).

Scanning Transmission Electron Microscopy Image of CdSe Nanowires

STEM image



TEM by Dr. Ping Lu

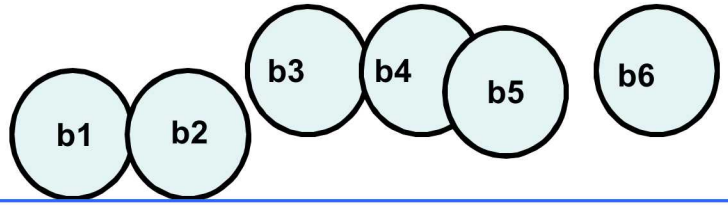


Height profile

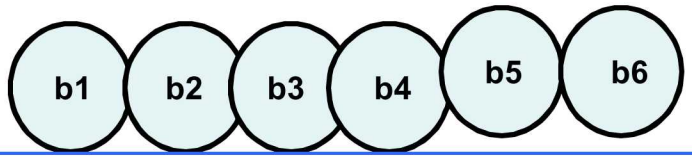
Along nanowire b

Nanowire (b)

Side view

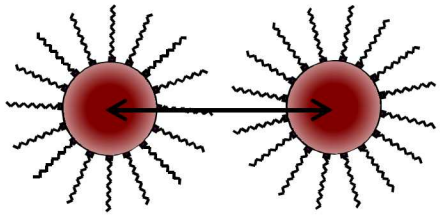


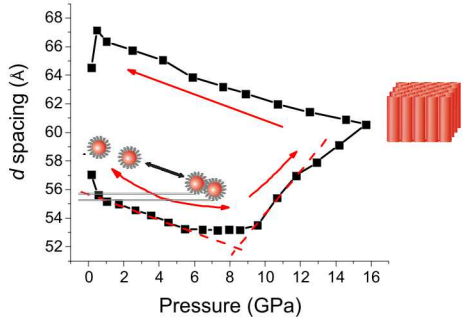
Top view

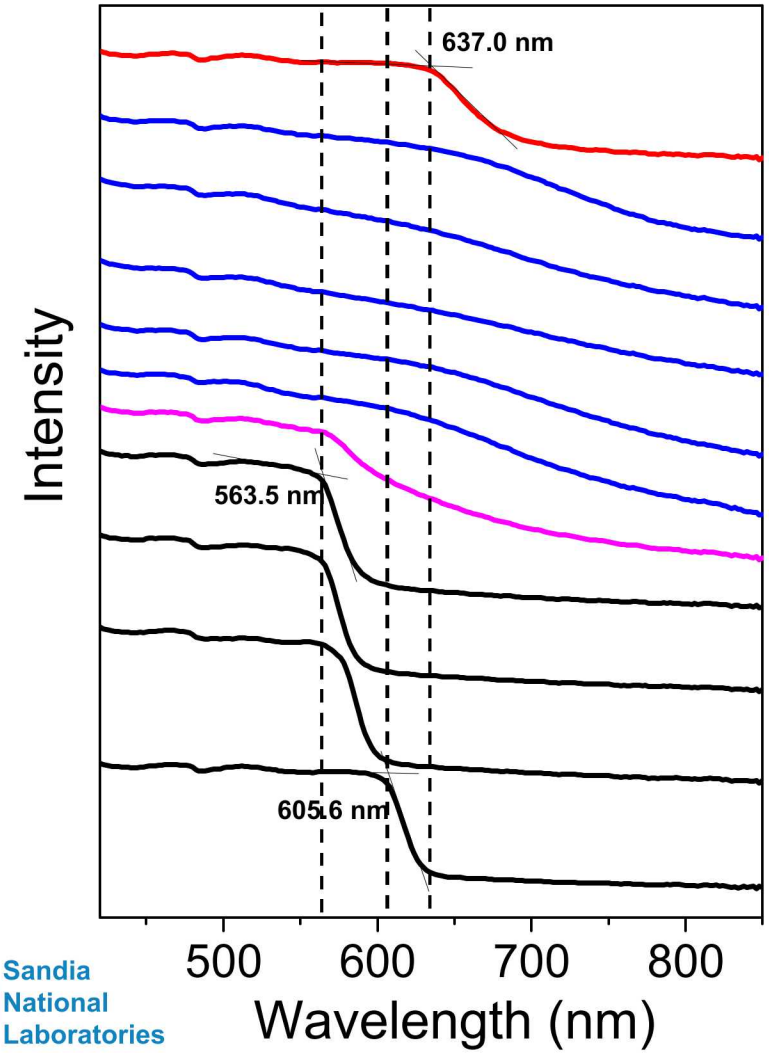


B. Li, K. Bian, et al, *Science Advances* 3, e1602916 (2017).

Stress Induced CdSe Nanoparticles Interactions







P (GPa)

R0 → Absorption peak became sharper and stronger. Absorption peak shows 31 nm red shift (from 605.6 nm to 637.0 nm).

R0.62, R4.51, 14.49, 8.03, 7.47 — Absorption peak further extends to longer wavelength (up to about 800 nm), indicating nanowires formation.

7.05 → Absorption peak starts to extend to longer wavelength at around 7 GPa, indicating the nanoparticles become consolidated.

6.32, 4.62, 2.67, 0 — Absorption peak blue shifts due to nanoparticle aggregation under pressure. The peak blue-shifts until pressure reaches to 4.62GPa, then remains almost no change until 6.32GPa, indicating the nanoparticles become very close or start to contact at ~ 4.62GPa.

B. Li, K. Bian, et al, *Science Advances* 3, e1602916 (2017).

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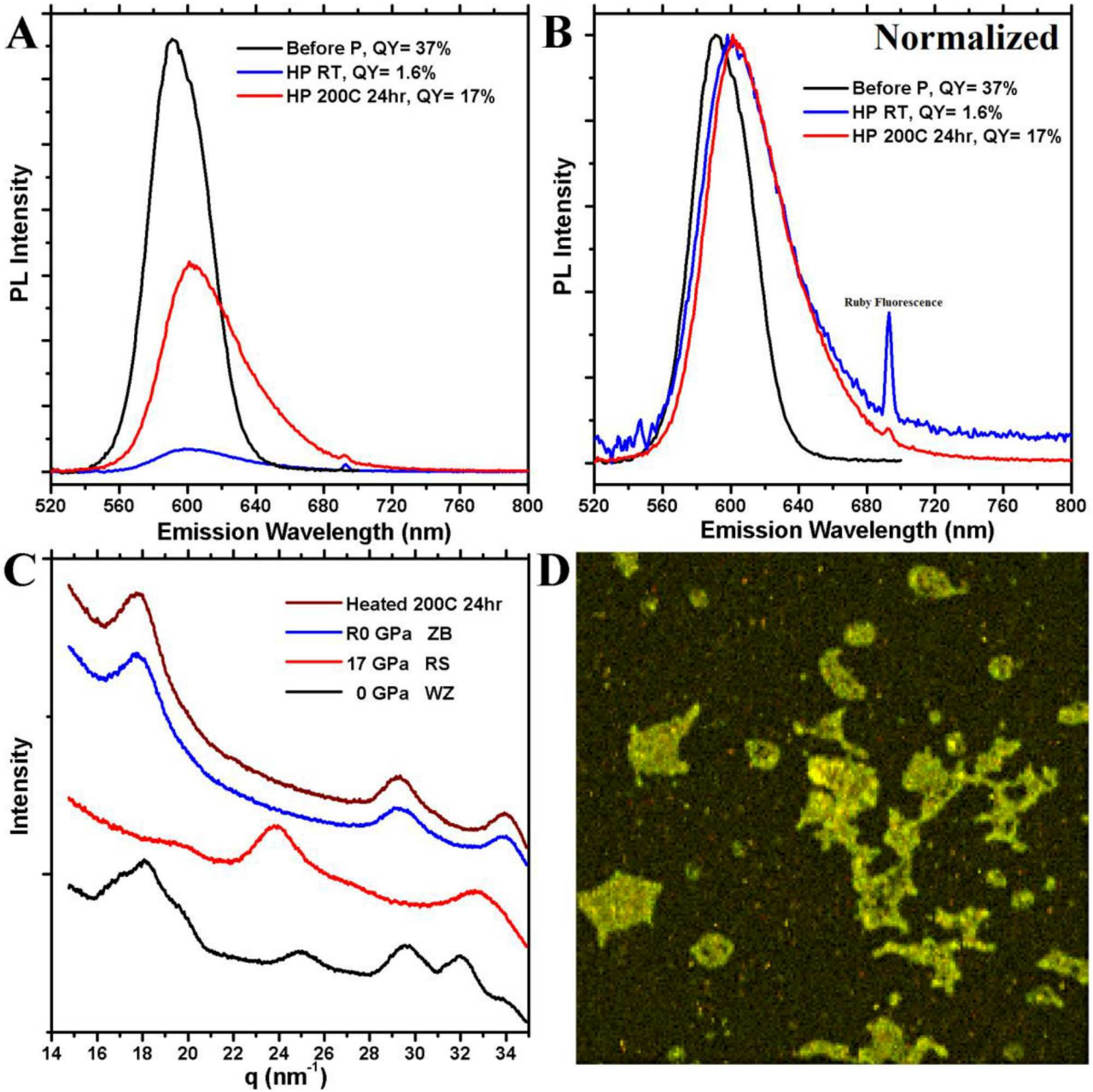
Optical Property of CdSe Nanowires



B. Li, K. Bian, et al, *Science Advances* 3, e1602916 (2017).

nature COMMUNICATIONS

ARTICLE

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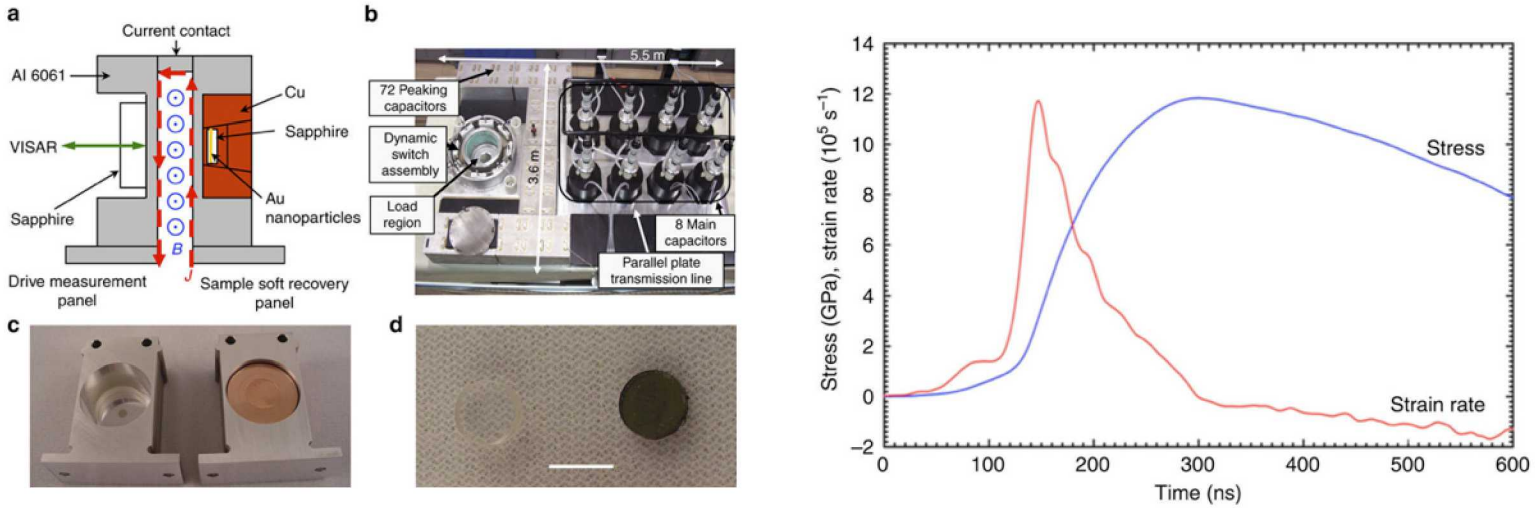
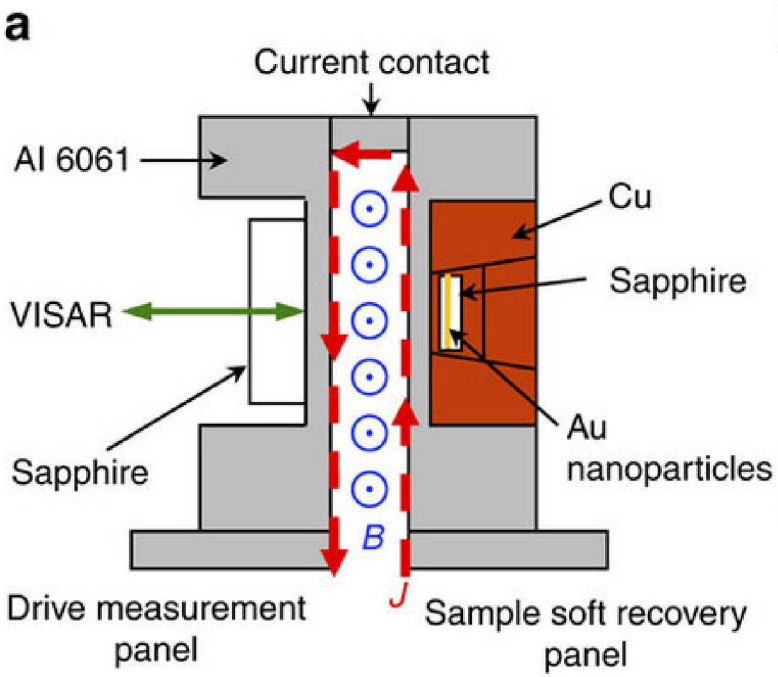
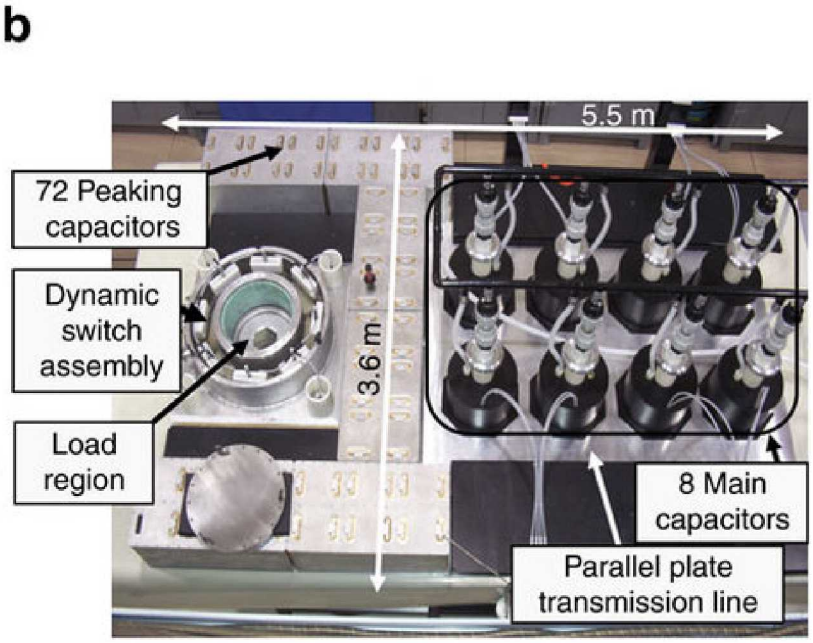
Superfast assembly and synthesis of gold nanostructures using nanosecond low-temperature compression via magnetic pulsed power

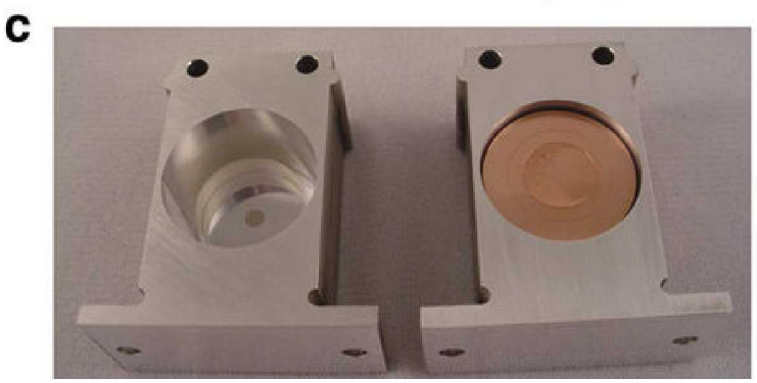
Binsong Li[1,*], Kaifu Bian[1,*], J. Matthew D. Lane[1], K. Michael Salerno[1], Gary S. Grest[1], Tommy Ao[1], Randy Hickman[1], Jack Wise[1], Zhongwu Wang[2] & Hongyou Fan[1,3,*]

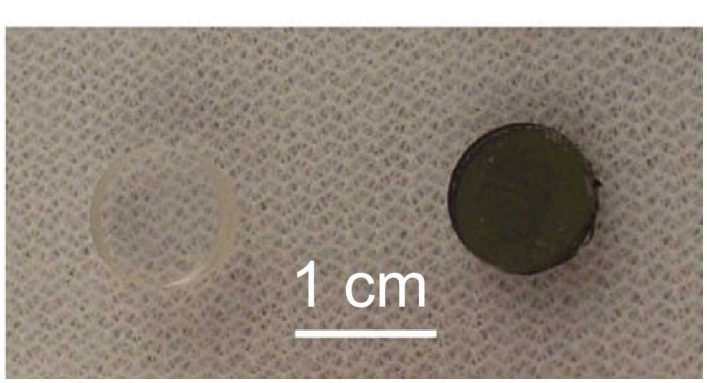


Ultrafast assembly and synthesis of gold nanostructures using nanosecond compression via pulsed power









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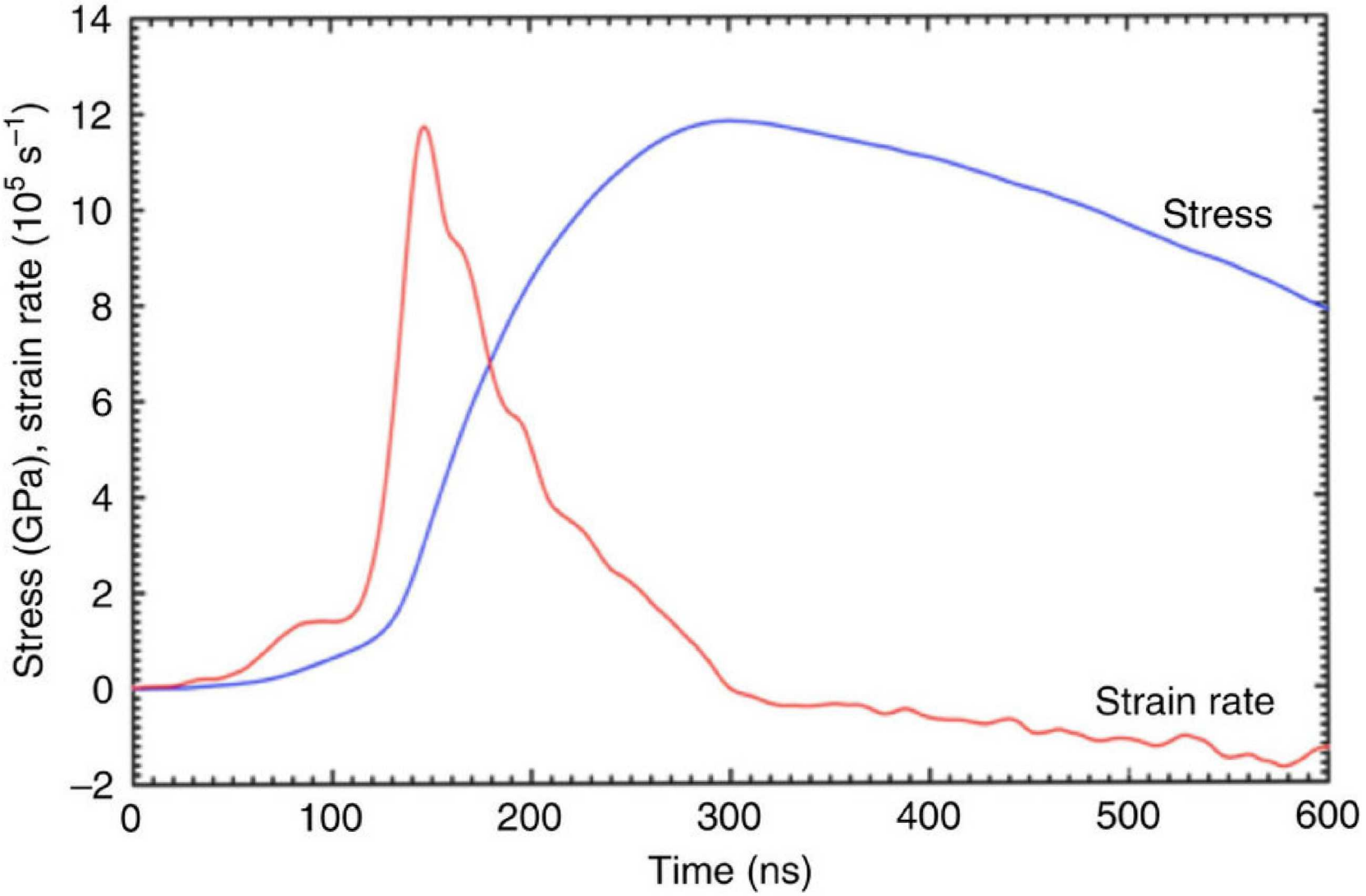
Li, B. et al. *Nat. Commun.* 8, 14778 doi: 10.1038/ncomms14778 (2017).

Ultrafast assembly and synthesis of gold nanostructures using nanosecond compression via pulsed power



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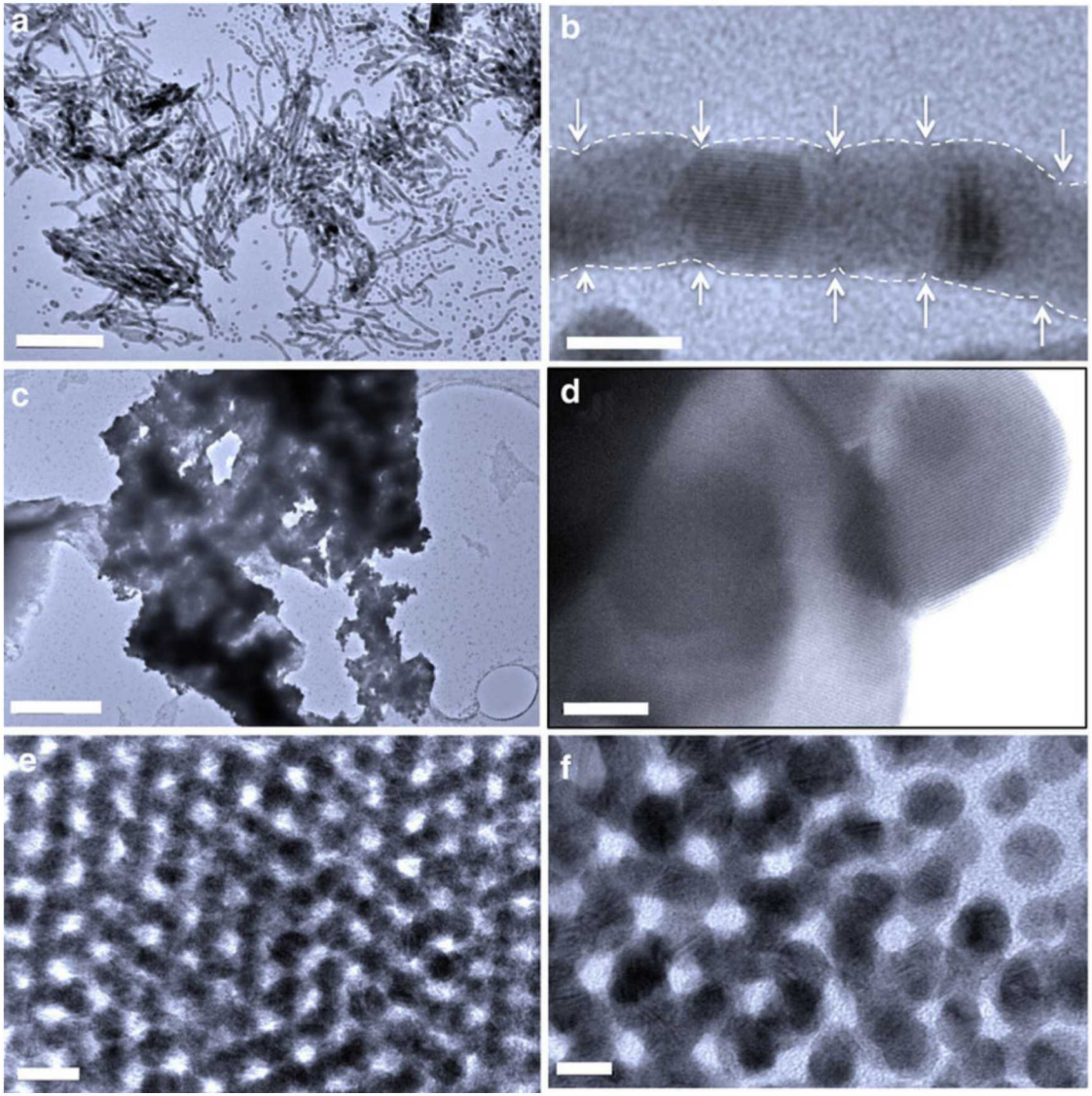
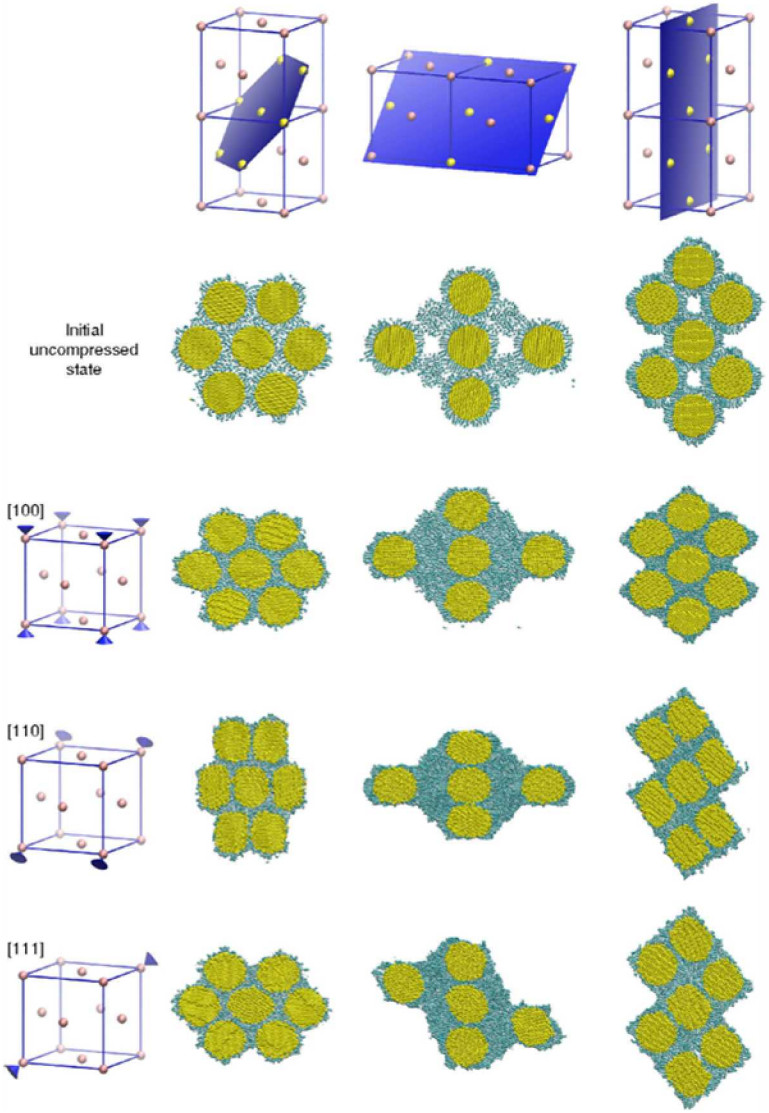
Li, B. et al. *Nat. Commun*. 8, 14778 doi: 10.1038/ncomms14778 (2017).

Ultrafast Assembly and Synthesis of 1-3D Nanostructures within Nanoseconds via Pulsed Power



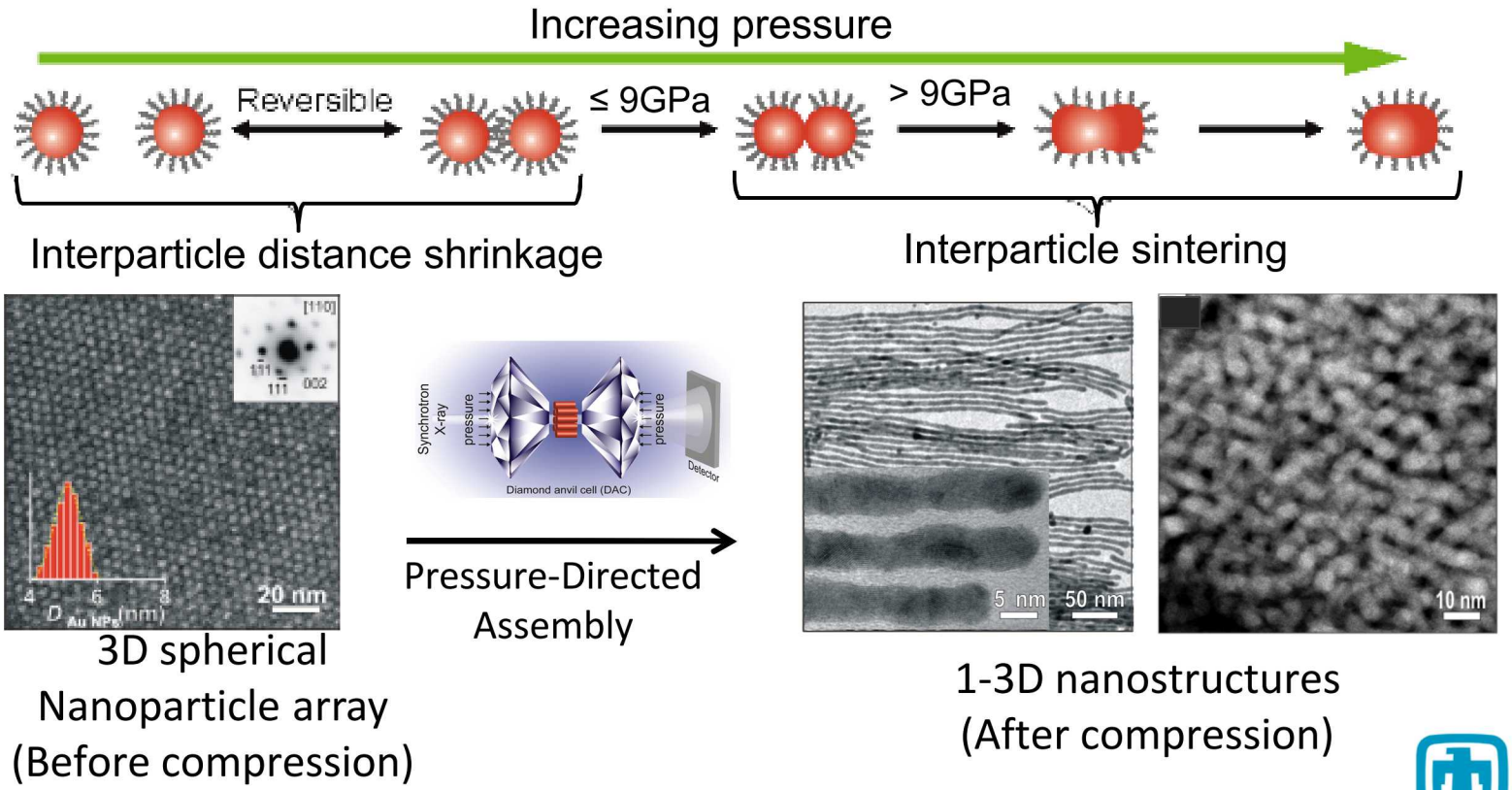


Li, B. et al. *Nat. Commun*. 8, 14778 doi: 10.1038/ncomms14778 (2017).

Summary: Pressure-Induced Nanoparticle Engineering

Pressure-Directed Assembly presents a paradigm shift in engineering nanoparticle arrays:

- Allow precise, systematic, and reversible tuning of interparticle distance for interrogation of new chemical and physical properties.
- Produce new chemically and mechanically stable 1-3D nanostructures, which is not possible for current top-down and bottom up methods.



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CHEMICAL REVIEWS

Review

Cite This: Chem. Rev. 2019, 119, 7673−7717

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Pressure Induced Nanoparticle Phase Behavior, Property, and Applications

Feng Bai,*,† Kaifu Bian,‡ Xin Huang,§ Zhongwu Wang,*,§ and Hongyou Fan*,‡,∥,⊥

†Key Laboratory for Special Functional Materials of the Ministry of Education, Henan University, Kaifeng 475004, P. R. China

‡Sandia National Laboratories, Albuquerque, New Mexico 87185, United States

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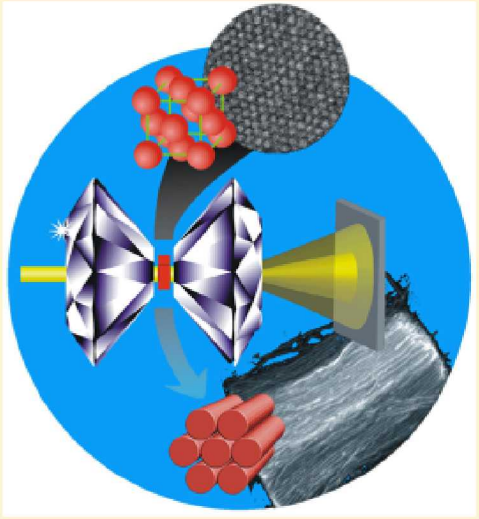
∥Department of Chemical and Biological Engineering, Albuquerque, University of New Mexico, Albuquerque, New Mexico 87106, United States

⊥Center for Integrated Nanotechnologies, Sandia National Laboratories, Albuquerque, New Mexico 87185, United States

ABSTRACT: Nanoparticle (NP) high pressure behavior has been extensively studied over the years. In this review, we summarize recent progress on the studies of pressure induced NP phase behavior, property, and applications. This review starts with a brief overview of high pressure characterization techniques, coupled with synchrotron X-ray scattering, Raman, fluorescence, and absorption. Then, we survey the pressure induced phase transition of NP atomic crystal structure including size dependent phase transition, amorphization, and threshold pressures using several typical NP material systems as examples. Next, we discuss the pressure induced phase transition of NP mesoscale structures including topics on pressure induced interparticle separation distance, NP coupling, and NP coalescence. Pressure induced new properties and applications in different NP systems are highlighted. Finally, outlooks with future directions are discussed.



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Team and Collaborators

Kaifu Bian (SNL)
Huimeng Wu (former SNL postdoc)
Binsong Li (former SNL postdoc)
Zaicheng Sun (former UNM postdoc)
Feng Bai (former UNM postdoc)
Raid Haddad (former UNM graduate student)

Sheng Liu (Sandia National Lab)
Wilie Luk (Sandia National Lab)
Igal Brener (Sandia National Lab)
Mike Sinclair (Sandia National Lab)
Ping Lu (Sandia National Lab)
Zhongwu Wang (Cornell University, CHESS)

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