Basic 7
Micro-Nano Assembly

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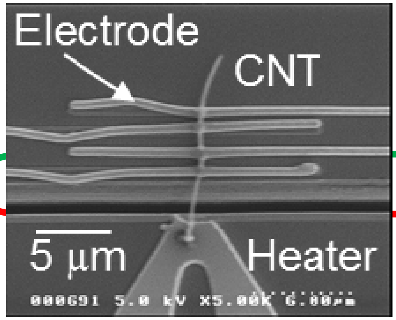
Contents

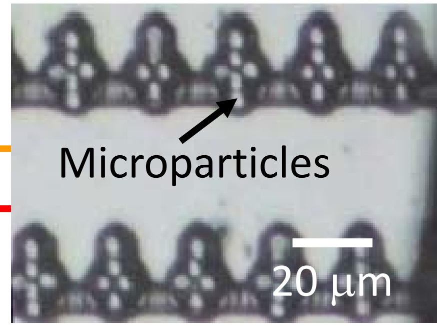
Techniques for Micro-Nano Assembly

Micro-Nano Manipulation

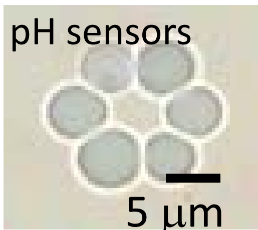
- Contact (Mechanical, Electrostatic, Wan der Waals, etc.)
- Noncontact (Optical, Electrostatic, Magnetic, etc.)



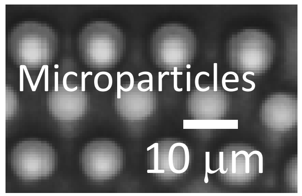
Micro-Nano Assembly



- Self-adhesive material
- Optical connection
- Welding



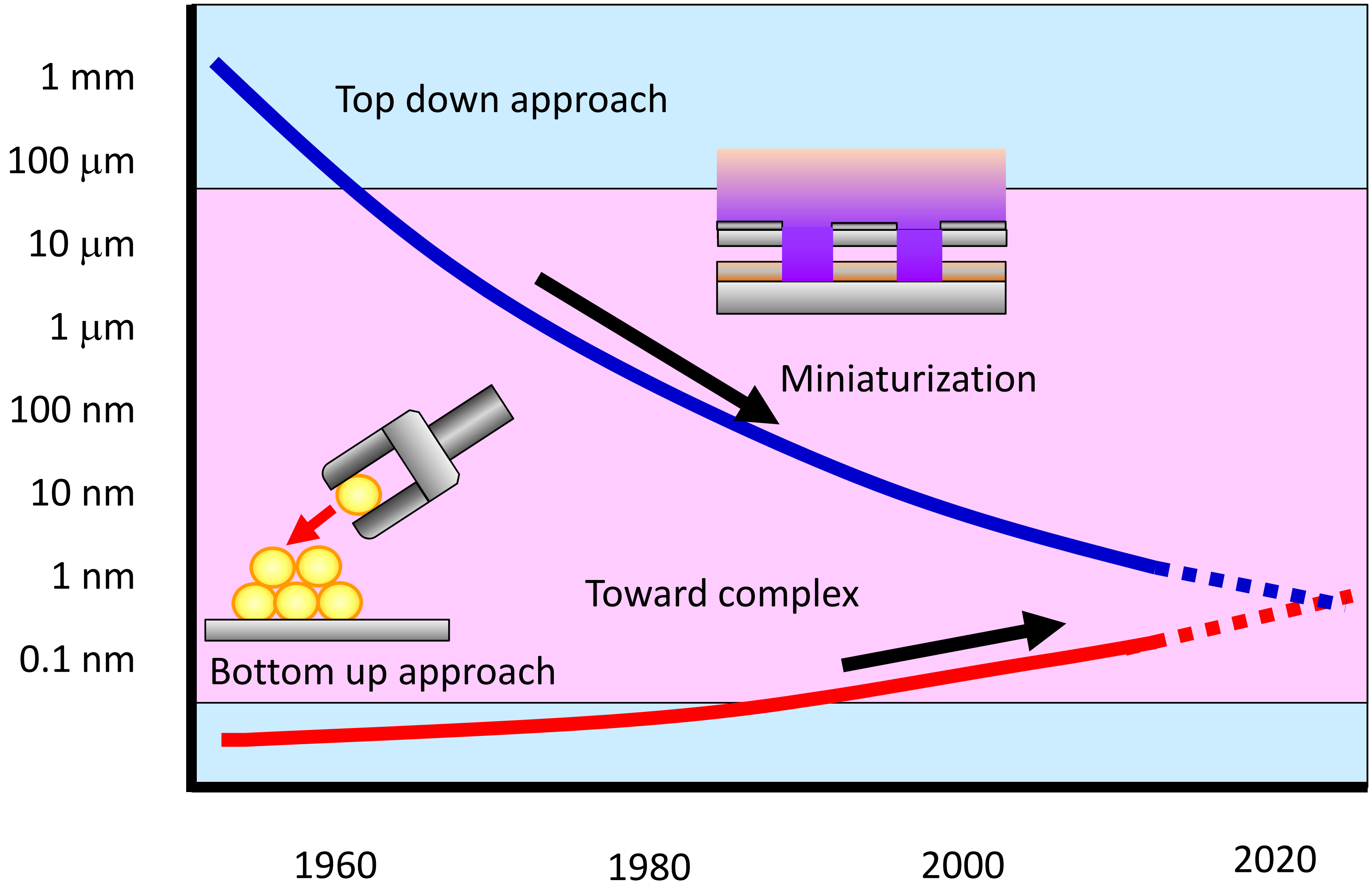
- Chemical and Phyisical
- Physical
- Chemical



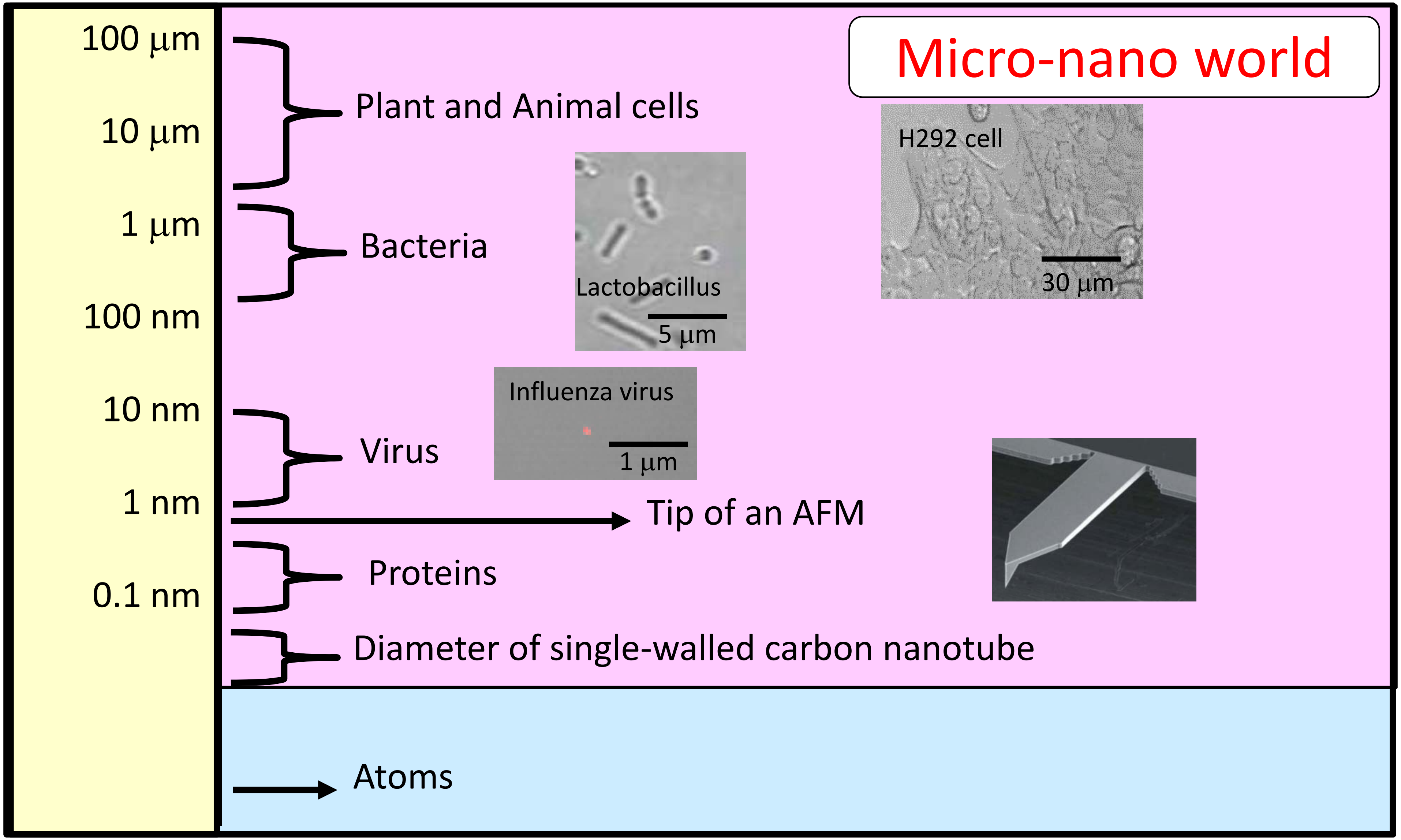
Connection

Self-assembly

Approach of Micro-Nano Technology



Size and scale of structures in Micro-Nano World

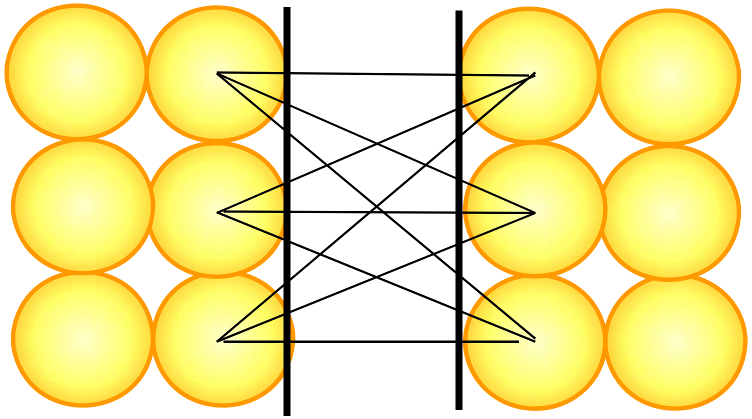


Comparison of Workspace (Microscope)

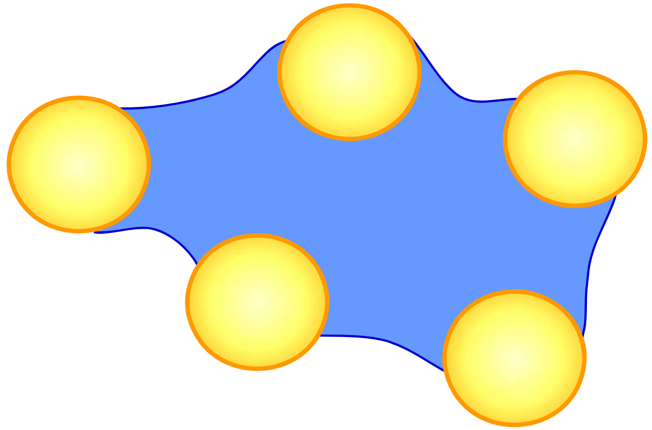
Properties	Items	AFM	STM	SEM	OM
Manipulation	Interaction with object	Contact Noncontact Intermittent contact	noncontact	Noncontact	Noncontact
Imaging	Imaging principle	Interatomic force	Tunneling current	Electron emission	Light-matter interaction
	Visual resolution	> 0.1 nm	> 0.1 nm	> 1 nm	> 100 nm
	Objective type	All	Conductor Semi-conductor	Conductor Semi-conductor	All
	Dimensions	3D	3D	2D	2D
Real-time sensing		Force/image	Image	Image	Image

Interactive Force in Micro-Nano Word

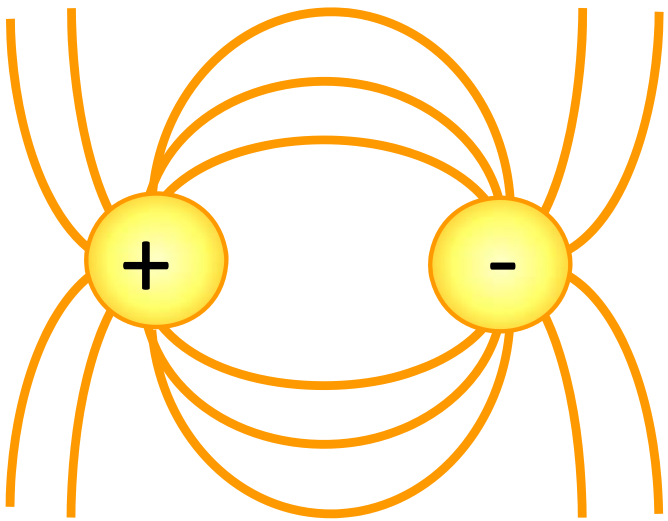
(a) Van der Waals force



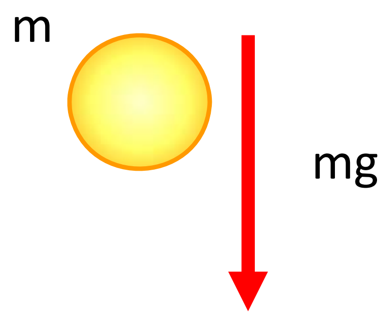
(b) Liquid bridge force



(c) Electric force



(d) Gravity force



Wan der Waals Force

Energy of interaction between atoms (ex. Dispersion effect)

$$\varepsilon = -\frac{\Lambda}{z^6}$$

z: distance between atoms
Λ: London-wan der Waals constant

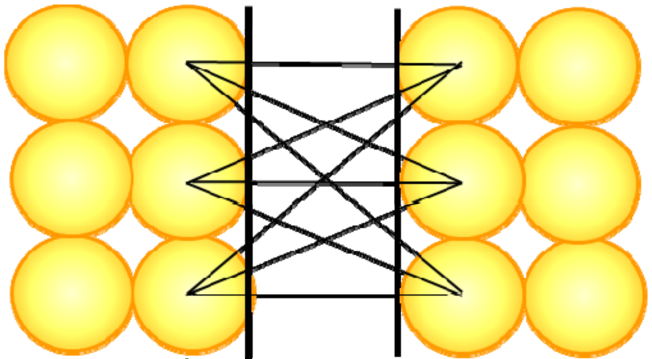
Energy of interaction between particles

$$E = -\int_{V_1} d\tau_1 \int_{V_2} d\tau_2 \frac{n^2 \Lambda}{z^6}$$

V_1, V_2: volume of particles
n: number of atoms

Van der walls force

$$F_{vdw} = \frac{\partial E}{\partial z}$$



Volume integration

Wan der Waals Force

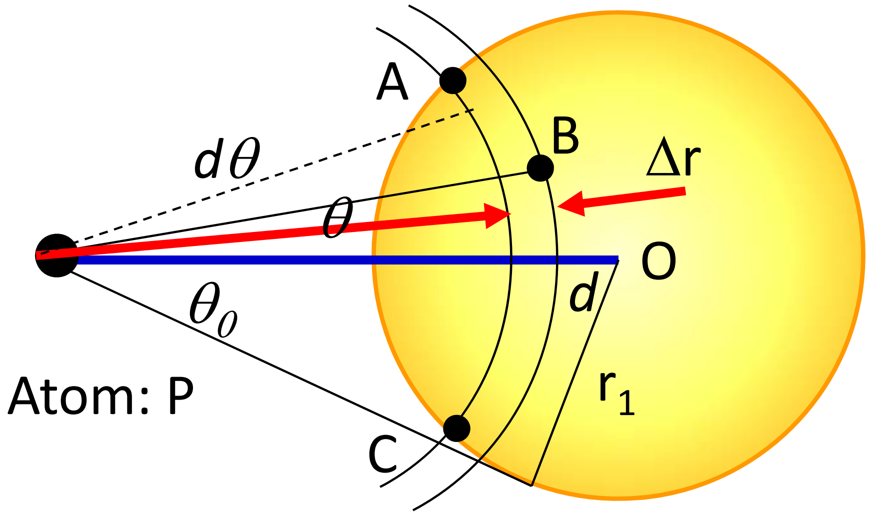
1. Theory of Hamaker

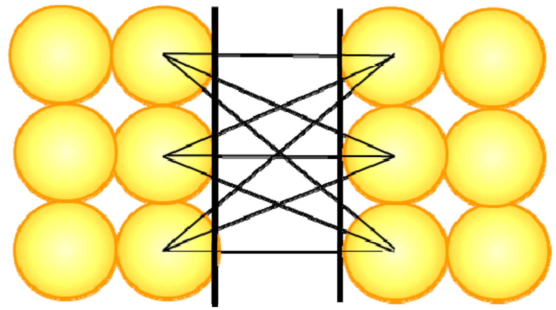
Interaction between two objects is acquired by adding interactions between all molecules.

2. Theory of Lifshitz

Interaction between molecules is followed by London force.

$$\varepsilon = -\frac{\Lambda}{z^6}$$





$$S_{ABC} = \frac{\pi r}{d}\left\{r_1^{\ 2} - (d-r)^2\right\}$$

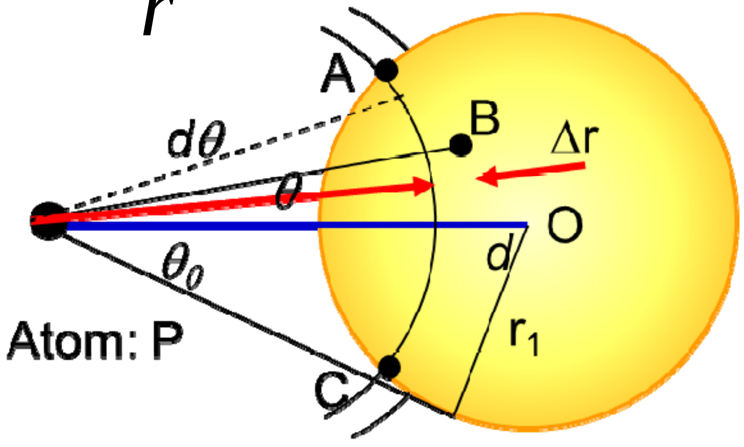
$$V_{ABC} = \frac{\pi r}{d}\left\{r_1^{\ 2} - (d-r)^2\right\}\Delta r$$

Wan der Waals Force

Wan der Waals energy between V_{ABC} and P

$$E_{ABC-P} = \frac{\pi r}{d}\left\{r_1^{\ 2} - (d-r)^2\right\}\Delta r \cdot n \frac{\Lambda}{r^6}$$

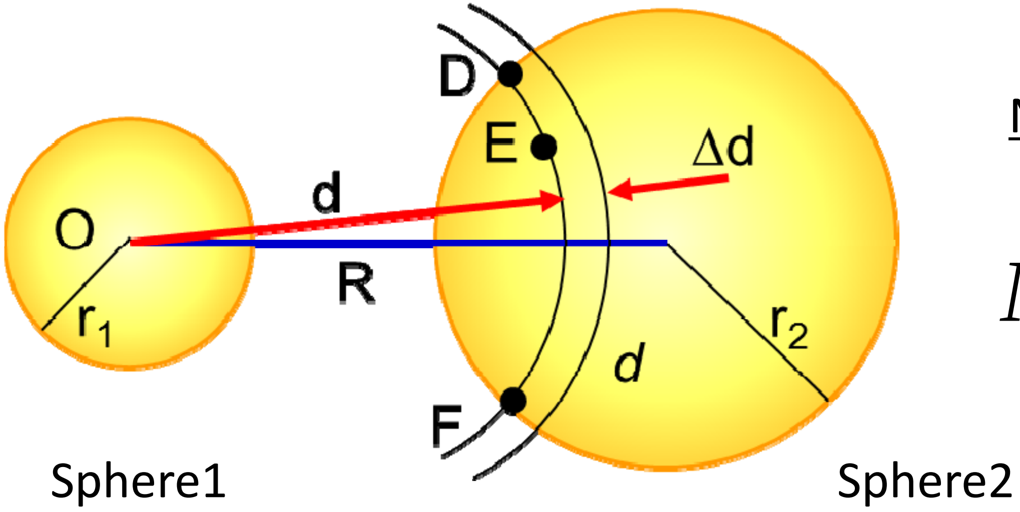
"n" per unit volume



Wan der Waals energy between Sphere1 and P

$$E_{1-P} = -\int_{d-r_1}^{d+r_1} \frac{\Lambda \pi n}{d} \cdot \frac{1}{r^5}\left\{r_1^{\ 2} - (d-r)^2\right\}\Delta r$$

Wan der Waals Force



Number of atoms in V_{DEF}

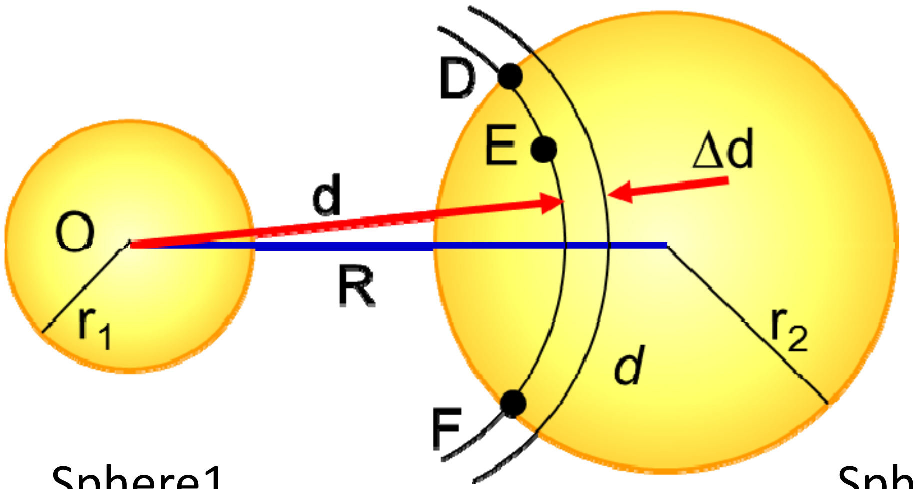
$$N_{VDEF} = \frac{\pi n d}{R}\left\{r_2^{\ 2} - (R-d)^2\right\}\Delta d$$

Wan der Waals energy between Sphere1 and Sphere2

$$E_{1-2} = -\int_{R-r_2}^{R+r_2} E_{1-P}\cdot n\pi\frac{d}{R}\left\{r_2^{\ 2} - (R-d)^2\right\}\Delta d$$

$$= -\int_{R-r_2}^{R+r_2}\int_{d-r_1}^{d+r_1}\left\{r_1^{\ 2} - (d-r)^2\right\}\left\{r_2^{\ 2} - (R-d)^2\right\}\Delta r\Delta d$$

Wan der Waals Force



Sphere1

Sphere2

Wan der Waals energy between Sphere1 and Sphere2

$$E_{1-2} = E_{vdw} = -\frac{H}{6}\left\{ \frac{2r_1r_2}{R^2-(r_1+r_2)^2} + \frac{2r_1r_2}{R^2-(r_1-r_2)^2} + \ln\frac{R^2-(r_1+r_2)^2{}_2}{R^2-(r_1-r_2)^2} \right\}$$

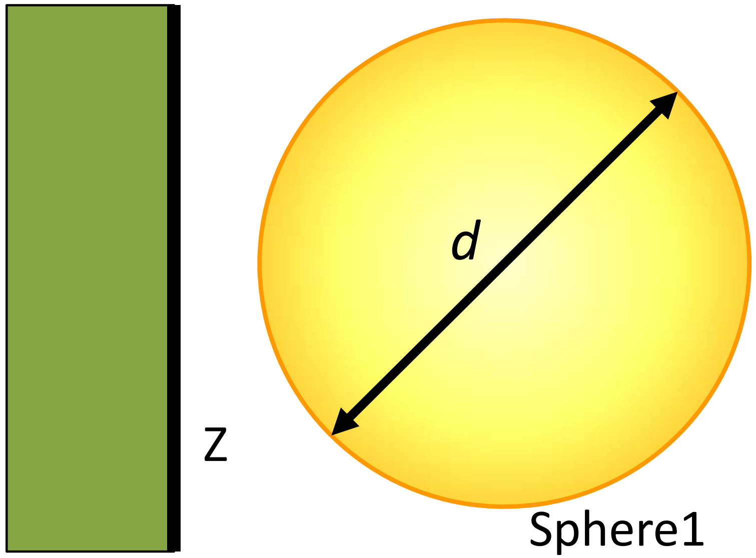
$$H = n^2\pi^2\Lambda$$ Hamaker constant

Wan der Waals Force

$r_2 \to \infty$ "r_1" is rewritten to "d"

Wan der Waals energy between Sphere1 and wall

$$E_{vdw} = -\frac{H}{6}\left\{\frac{d}{2z} + \frac{d}{2(z+d)} + \ln\frac{Z}{z+d}\right\}$$



Differentiate it with respect to z

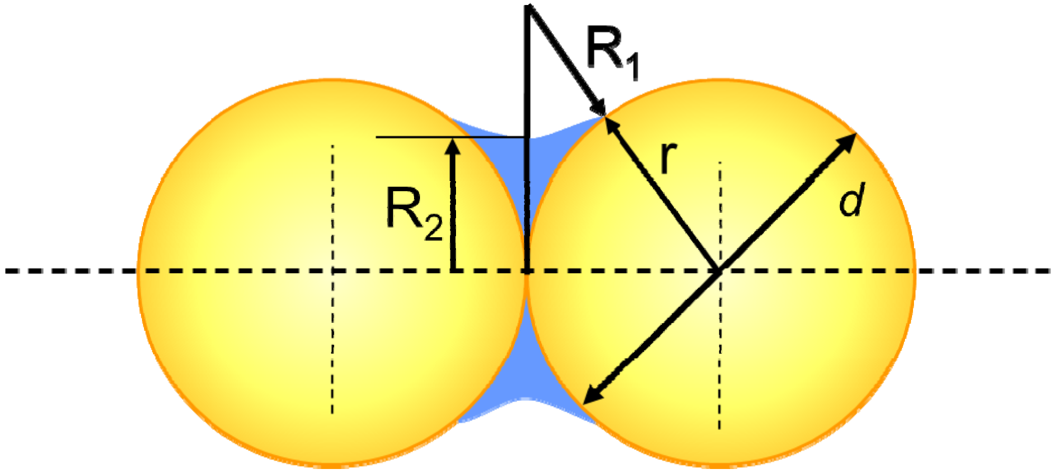
Wan der Waals force

(z << d)

$$E_{vdw} = -\frac{H}{6}\left\{\frac{d}{2z} + \frac{1}{2} + \ln 0\right\}$$

$$F_{vdw} \approx \frac{Hd}{12z^2}$$

Liquid bridge force



$$\begin{cases} R_1 = r\left(\dfrac{1}{\cos\alpha} - 1\right) \\ R_2 = r \cdot \tan\alpha - R_1 \end{cases}$$

Liquid bridge force (Positive if p is negative)

$$F_s = \pi R_2{}^2 \sigma \left(\frac{1}{R_1} - \frac{1}{R_2} \right) + 2\pi R_2 \sigma$$

σ: Surface tension force

Capillary force effect:
Haines, 1925

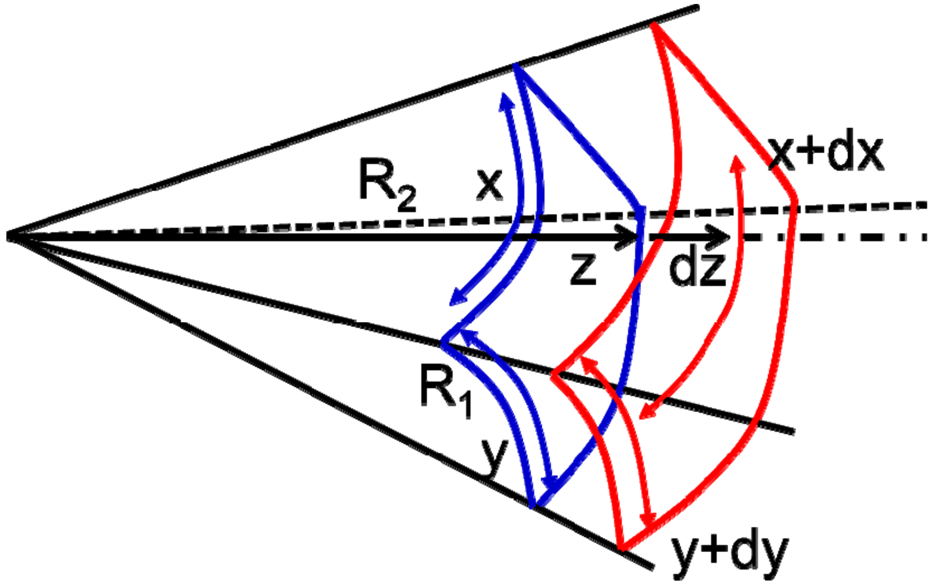
Surface tension effect
Fisher, 1926

$$F_s = \frac{\pi d \sigma}{1 + \tan(\alpha / 2)}$$

$\alpha \to 0$

$$F_s = \pi d \sigma$$

The Equation of Young and laplace



The surface is dispersed a small distance outwards.
The change in area:

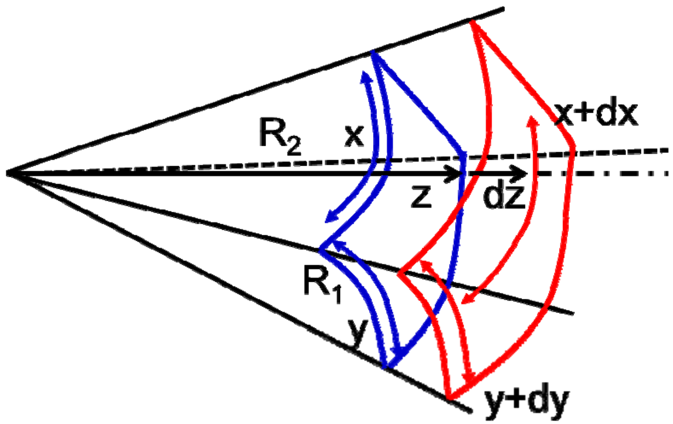
$$\Delta A = (x+dx)(y+dy) - xy = xdy + ydx$$

The work done in forming this amount of surface:

$$Work = \sigma \cdot \Delta A = \sigma(xdy + ydx) = \Delta Pxydz$$

σ: Surface tension force, ΔP: pressure difference

The Equation of Young and laplace



$$Work = \sigma \cdot \Delta A = \sigma\left(xdy + ydx\right) = \Delta Pxydz$$

$$\frac{x+dx}{R_2+dz} = \frac{x}{R_2} \quad \text{or} \quad dx = \frac{xdz}{R_2}, dxdz = 0$$

$$\frac{x+dx}{R_2+dz} = \frac{x}{R_2} \quad \text{or} \quad dy = \frac{ydz}{R_2}, dydz = 0$$

$$\Delta P = \frac{\sigma\left(xdy+ydx\right)}{xydz} = \sigma\left(\frac{dy}{ydz} + \frac{dx}{xdz}\right) = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

Electrostatic force

1. Coulomb force

$$Fe = \frac{\pi \sigma_1 \sigma_2 d^2}{\varepsilon_0}$$

ε_0 Permittivity in vacuum

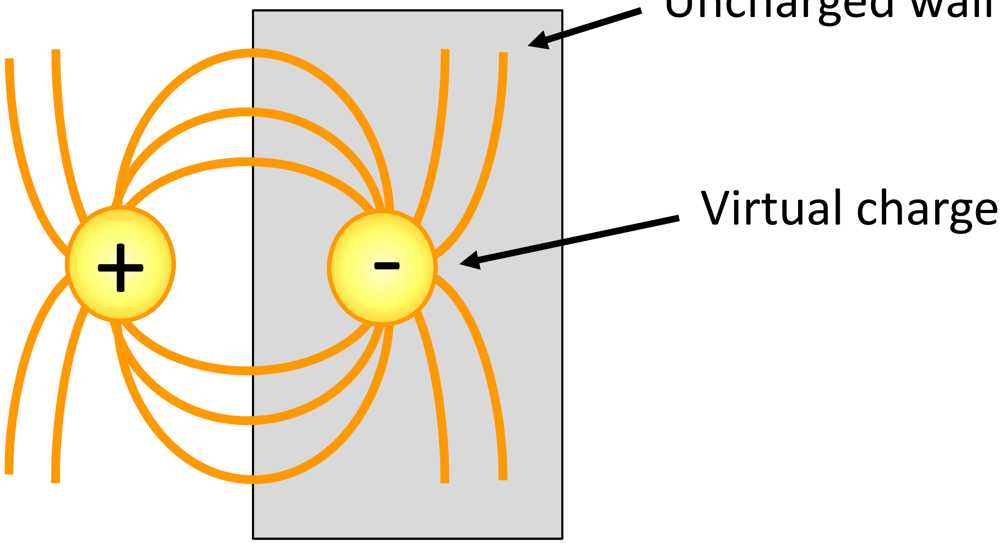
σ_1, σ_2 Surface charge density

ε Permittivity of object

ε_s Permittivity of solution

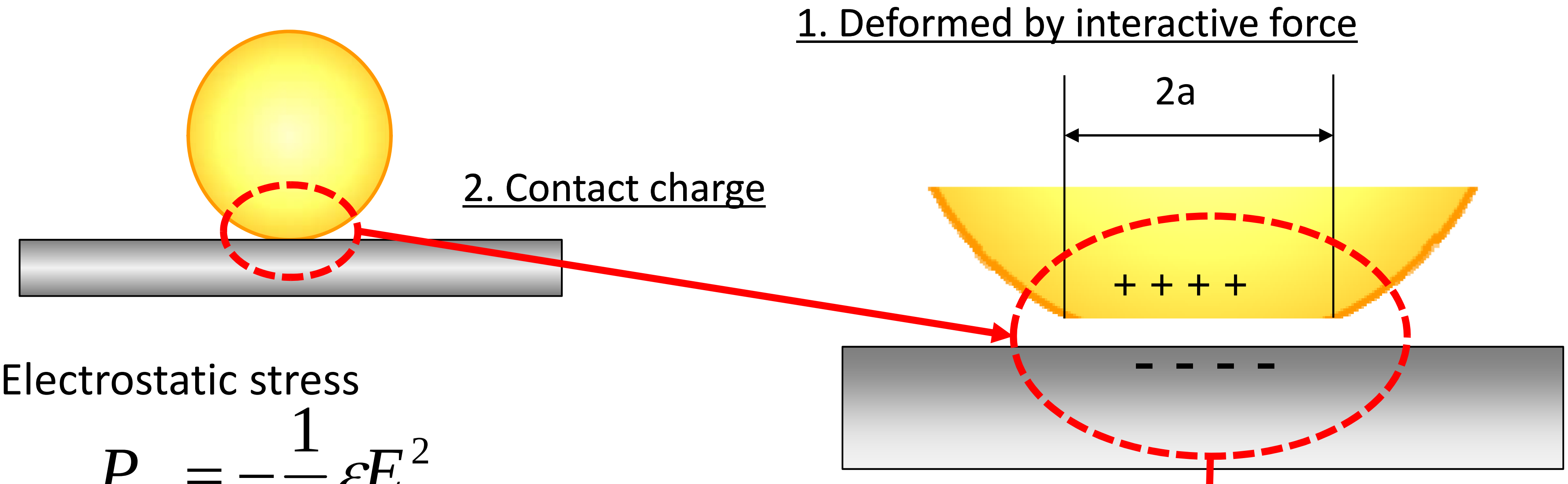
2. Electric image force

$$Fei = \frac{\pi}{4\varepsilon_0} \frac{\varepsilon - \varepsilon_s}{\varepsilon + \varepsilon_s} d^2 \sigma^2$$



3. Contact charging

Electrostatic force by Contact Charging

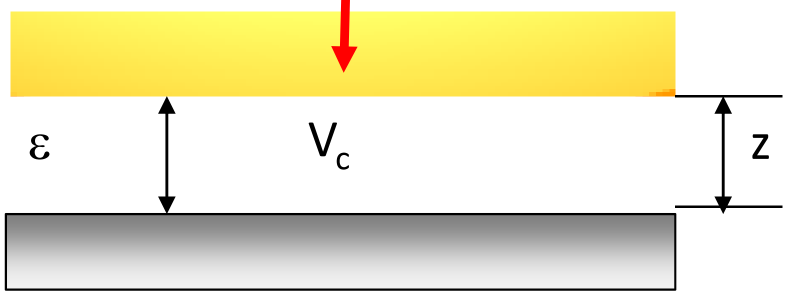


Electrostatic stress

$$P_{ce} = -\frac{1}{2}\varepsilon E^2$$

$$P_{ce} = -\frac{\varepsilon V_c^2}{2z^2}$$

$$E = \frac{V_c}{z}$$



$$S = \pi a^2$$

Hertz's constant stress theory

$$a = \left(\frac{3Fkd}{8}\right)^{\frac{1}{3}}$$

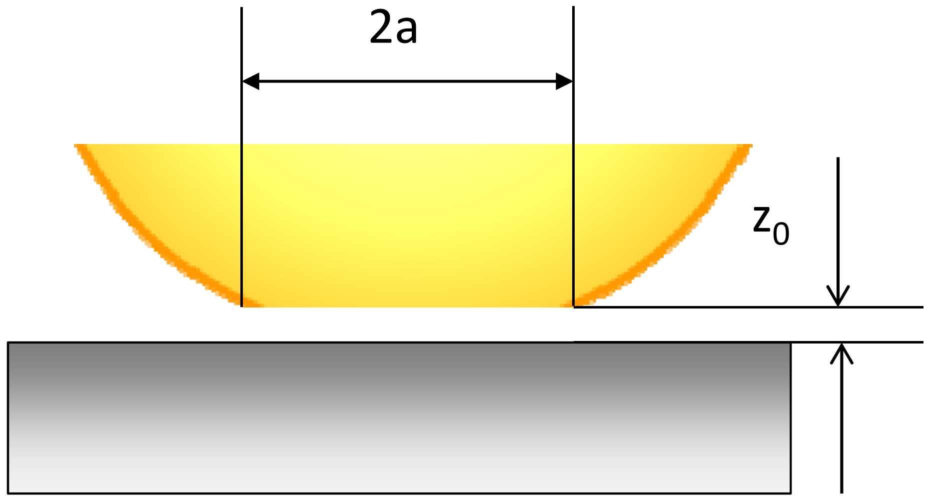
$$d = \frac{D_{p1}D_{p2}}{D_{p1}+D_{p2}}$$

$$k = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$$

Electrostatic force by Contact Charging

Van der Waals force

$$F = -\left(\frac{Hd}{12{z_0}^2}\right)\cdot\left\{1+\left(\frac{A^2k^2}{108{z_0}^7}\right)d\right\}$$



Electrostatic force by constant charge

$$F_{ce} = P_{ce}S = P_{ce}\cdot\pi a^2 = P_{ce}\pi\left(\frac{3Fkd}{8}\right)^{\frac{2}{3}}$$

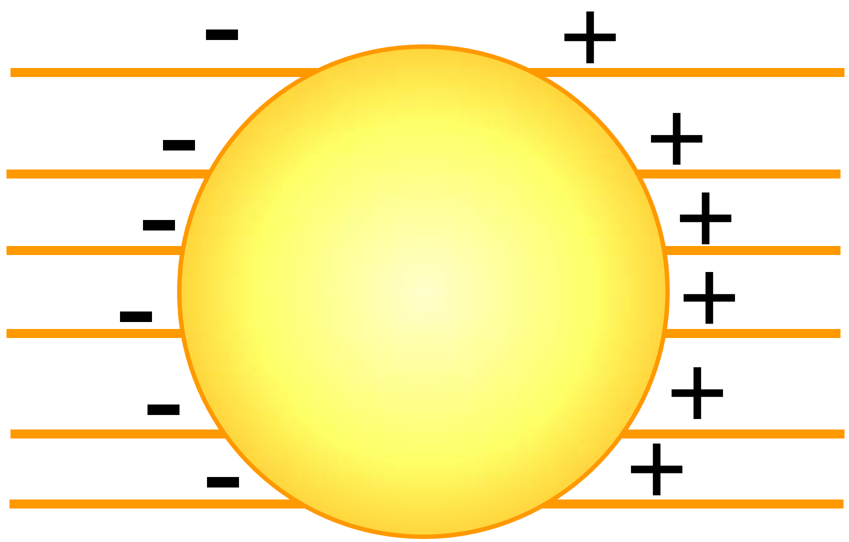
$$= -\frac{1}{2}\pi\varepsilon_0\frac{{V_c}^2}{{z_0}^2}\left\{\frac{Akd^2}{{z_0}^2}\left(1+\frac{A^2k^2d}{108{z_0}^7}\right)\right\}^{\frac{2}{3}}$$

Dielectrophoresis

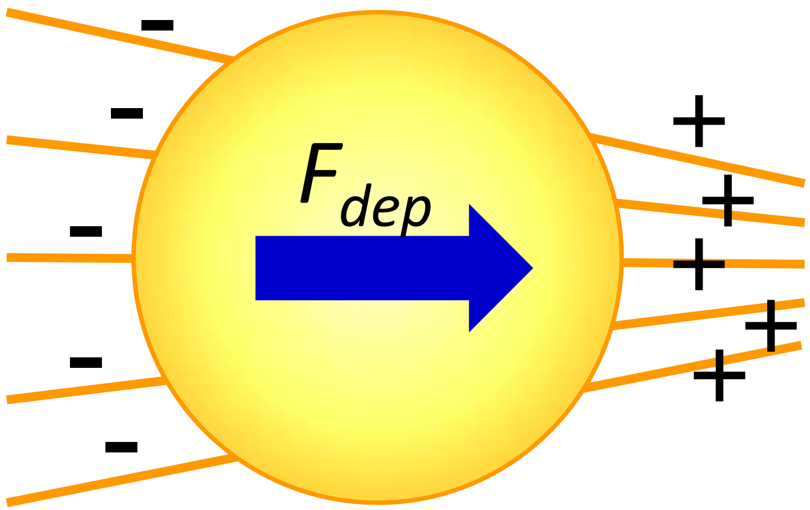
$$F_{dep} = \frac{1}{4}\pi d^3 \frac{\varepsilon_0(\varepsilon - \varepsilon_0)}{\varepsilon + 2\varepsilon_0}\nabla|E|^2$$

E	Electric field
ε	Permittivity of object
ε_s	Permittivity of solution

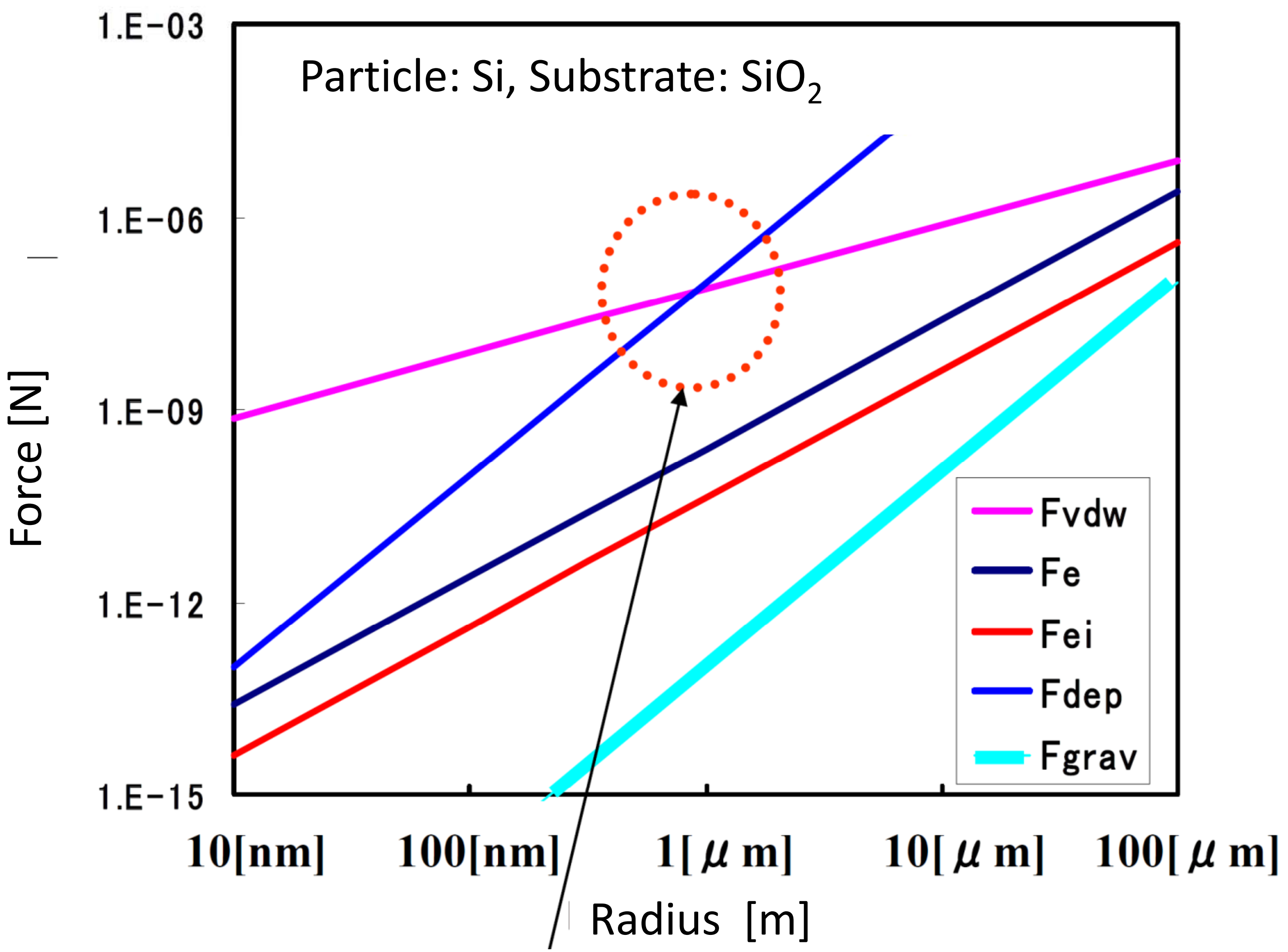
E=constant



E≠constant



Comparisons of interaction forces (Analytical)



Parameters

$H=14.8\times10^{-20}$ [J]

$\rho=2300$ [kg/m^3]

$z=0.4$ [nm]

$k= 2.0\times10^{-10}$ [m^2/N]

$\sigma=26.5$ [mC/m2]

$V_c=0.3$ [V]

$\varepsilon_0=8.85\times10^{-12}$ [F/m]

$\varepsilon_0=5\varepsilon_0$

<u>Radius < 1 μm</u>

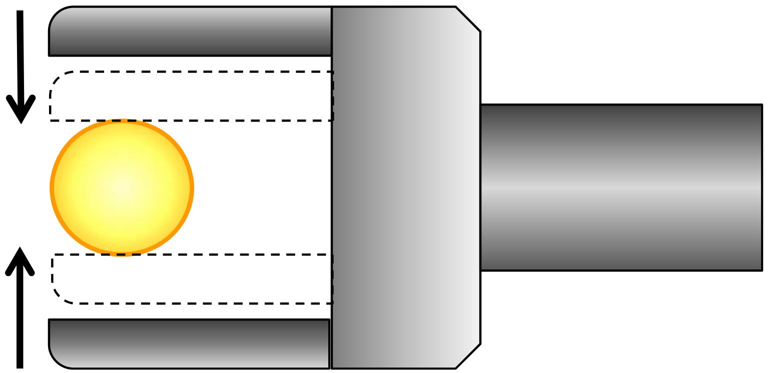
Van der Waals force is bigger than other forces.

Grouping of Micro-Nano Manipulation

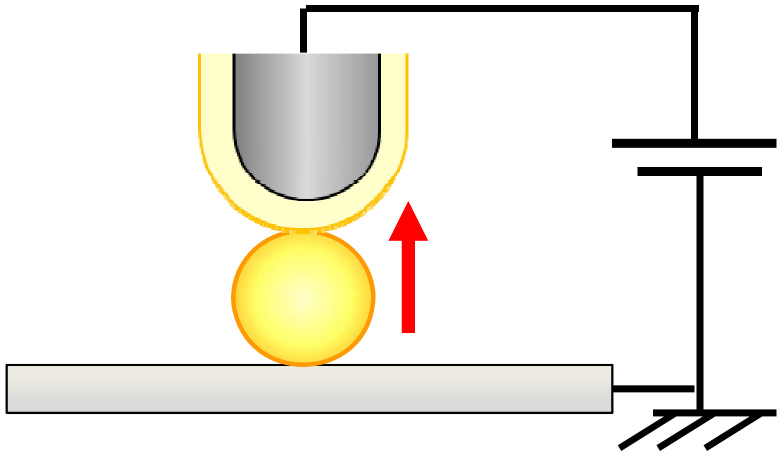
- Micro-Nanoscale Manipulation Approaches
  - Starting point
    - Top-down
    - Bottom up
  - Process
    - Self-assembly
    - Physical
  - Interaction Type
    - Contact
    - Noncontact
  - Operation
    - Automatic
    - Semi-automatic
    - Teleoperated

Contact Manipulation: Gripper/Grasping

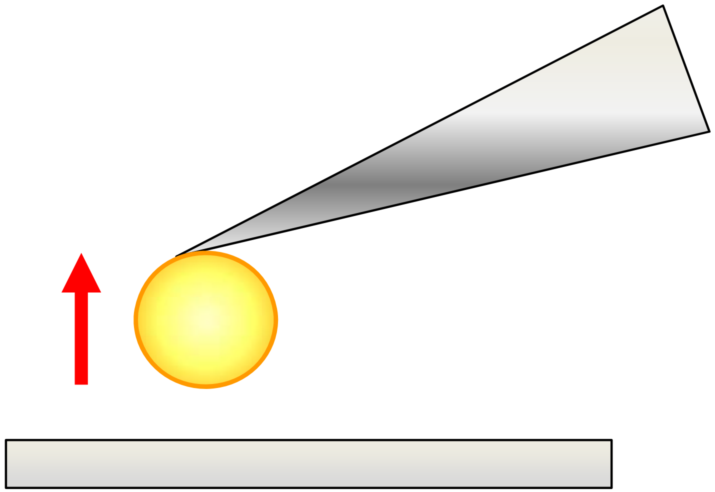
(a) Mechanical gripper



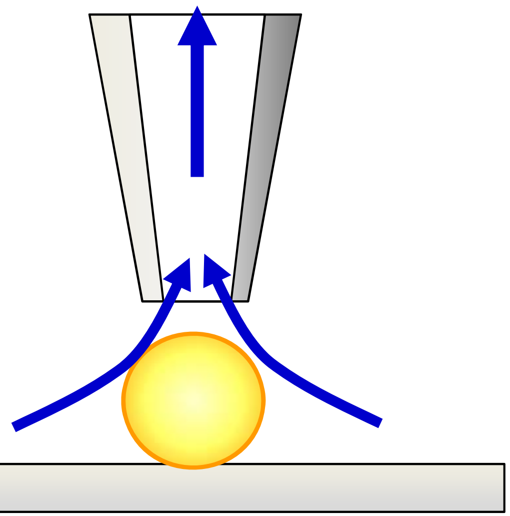
(b) Electrostatic gripper



(c) Wan der waals gripper

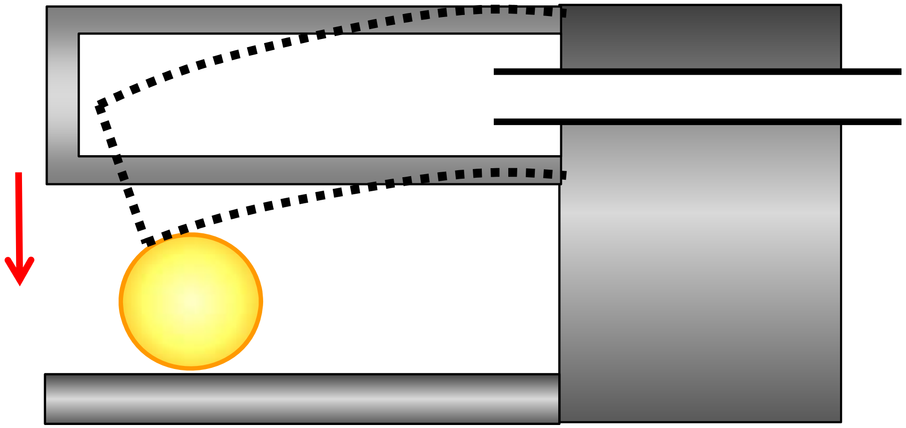


(d) Suction gripper

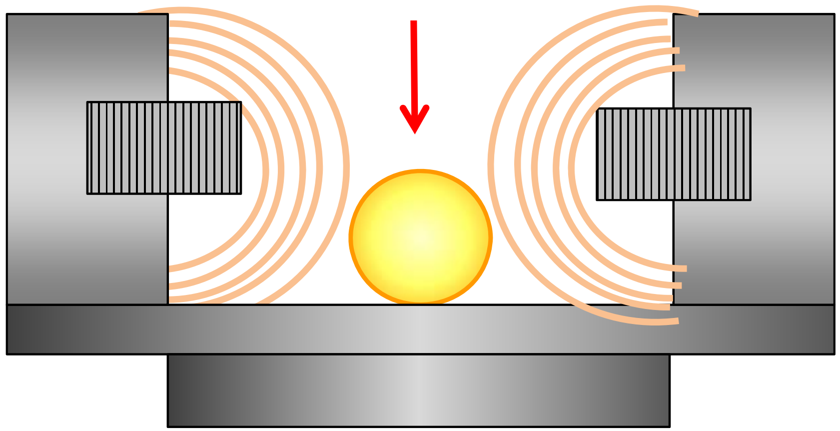


Contact Manipulation: Gripper/Grasping

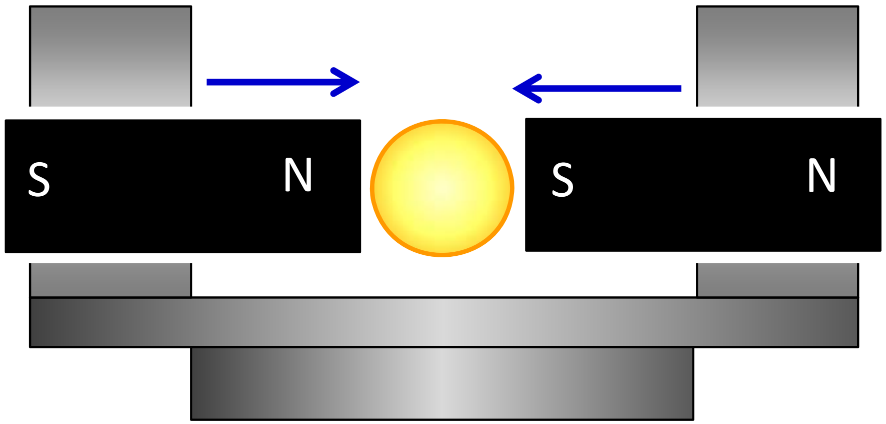
(e) Pneumatic gripper



(f) Wave pressure gripper

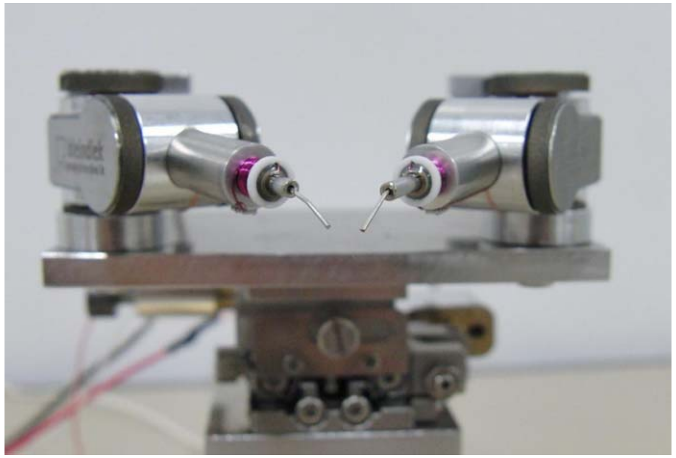


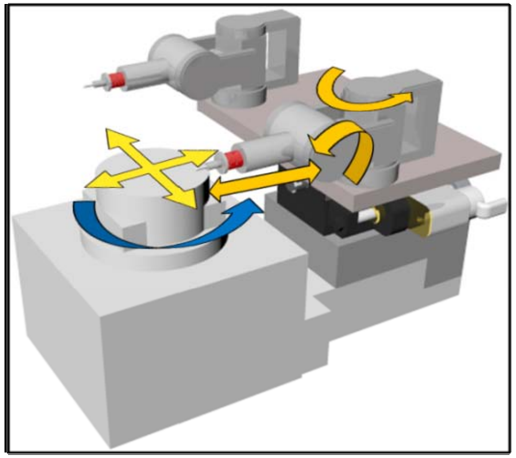
(g) Magnetic gripper



Wan der Waals Gripper (F. Arai, 2009)

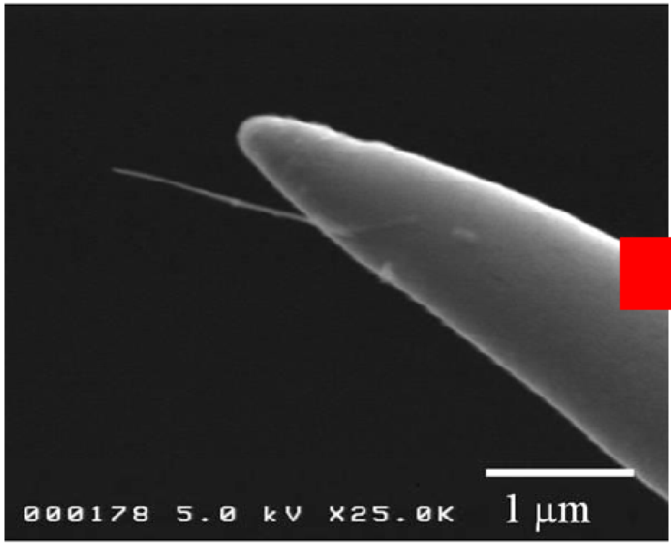
12-DOF nanomanipulation system



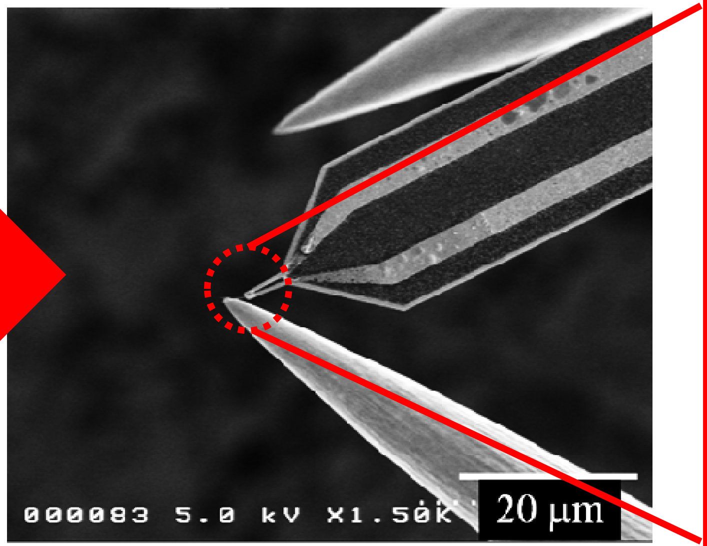


Positioning resolution
Pitch: 10-7 rad (5 nm)
Roll: 10-7 rad (3.5 nm)
Extension: 0.25 nm

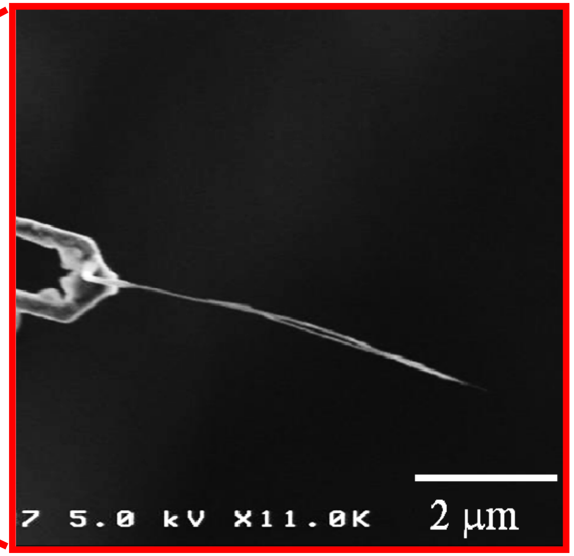
Nanoassembly of single CNT



Pick up of CNT



Connection to cantilever



Assembled CNT

F. Arai et. al., *IEEE NANO 2009*, 2009.

Non-Contact Manipulation: Optical Tweezers

Trapping force by optical tweezers

$$F = Q\frac{nP}{c}$$

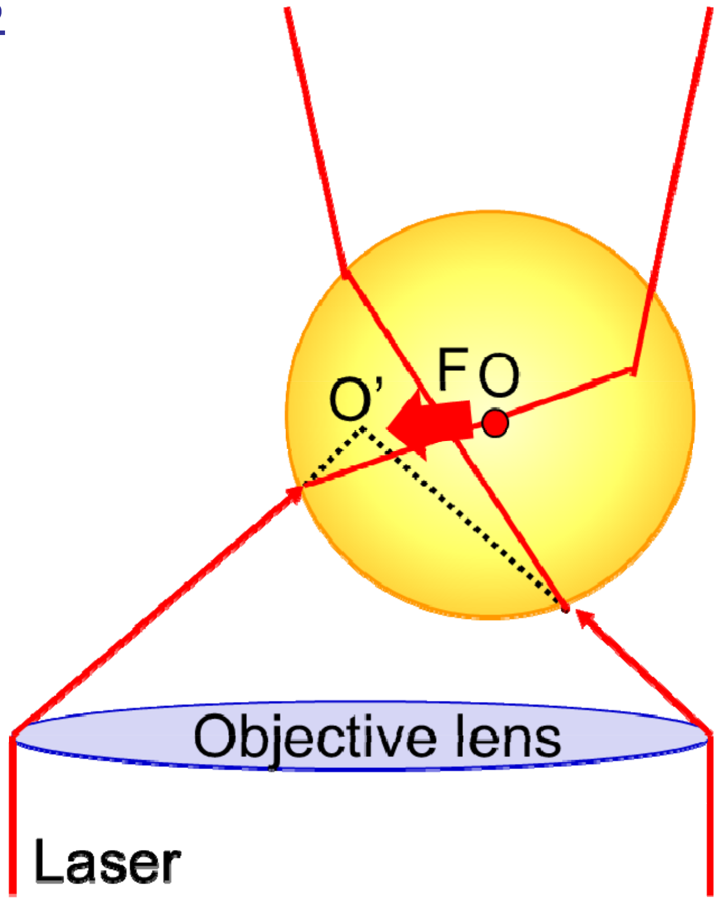
F : Trapping force [N]

Q : Trapping efficiency

n : Relative Refractive index

P : Light power [mW]

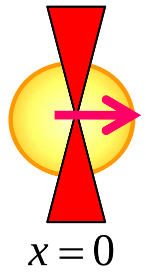
c : Light speed 3×10^{8}[m/s]



Target size:
From tens of nm to tens of μm

Ashkin A, et al,
Optics Letters, 1986

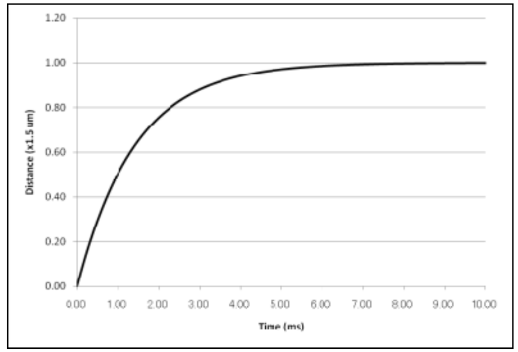
Stability Condition of Time Shared Scanning



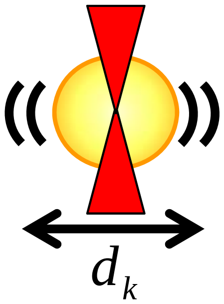
Settling Time : Minimum Time

Dynamics of Trapped Object

$$6\pi\eta r\dot{x} + Kx = 0$$



Step response of object



Brownian region of trapped beads

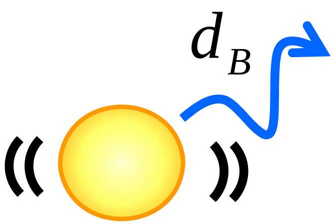
$$d_K = \sqrt{\frac{k_B T}{K}}$$

Stability Condition 1:

$$t_d \geq \frac{6\pi\eta r}{K} \ln\left(d_i \sqrt{\frac{K}{k_B T}} \right)$$

Free Time : Maximum Time

Total displacement by Brownian motion



Brownian motion

$$d_t = d_B + d_k = \sqrt{\frac{k_B T\{(n-1)t_d + nt_m\}}{3\pi\eta r}} + \sqrt{\frac{k_B T}{K}}$$

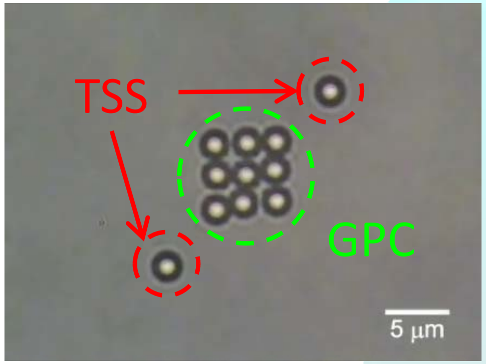
Non-trapped Trapped

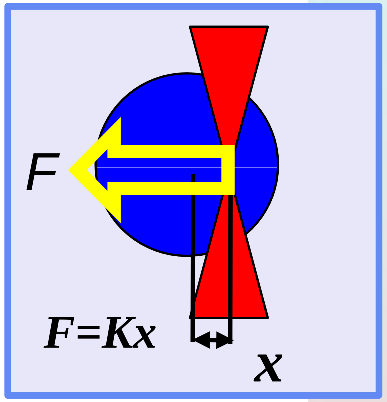
Stability Condition 2:

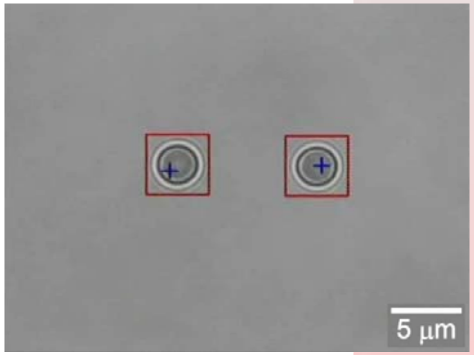
$$t_d \leq \frac{1}{n-1}\left\{ \frac{3\pi\eta r}{k_B T}\left(\frac{0.61\lambda}{N.A.} - \sqrt{\frac{k_B T}{K}} \right)^2 - nt_m \right\}$$

F. Arai et. al., *APL*, 85-19, 2004

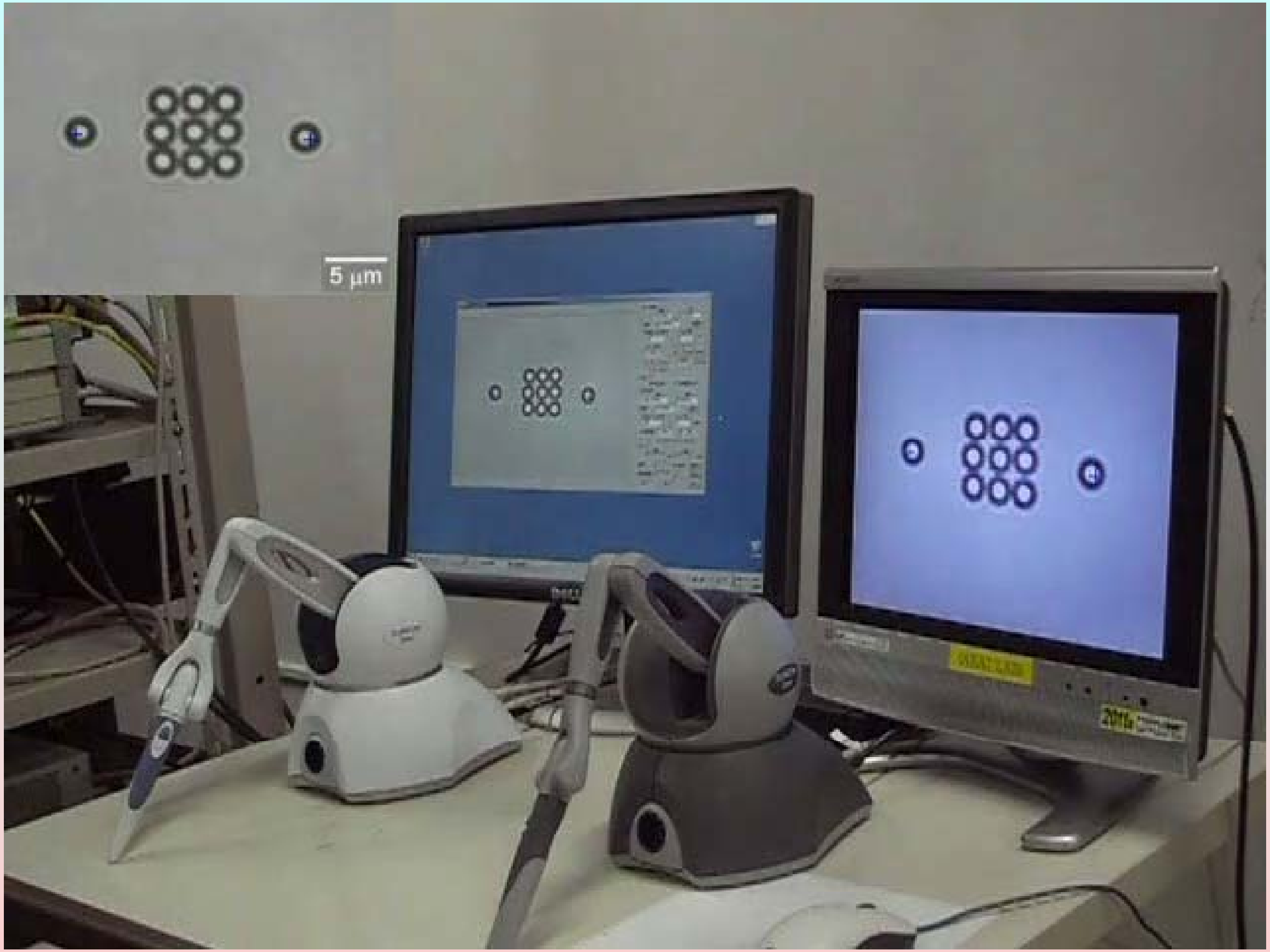
Optical Particle Manipulation (F. Arai, 2009)







Force feedback

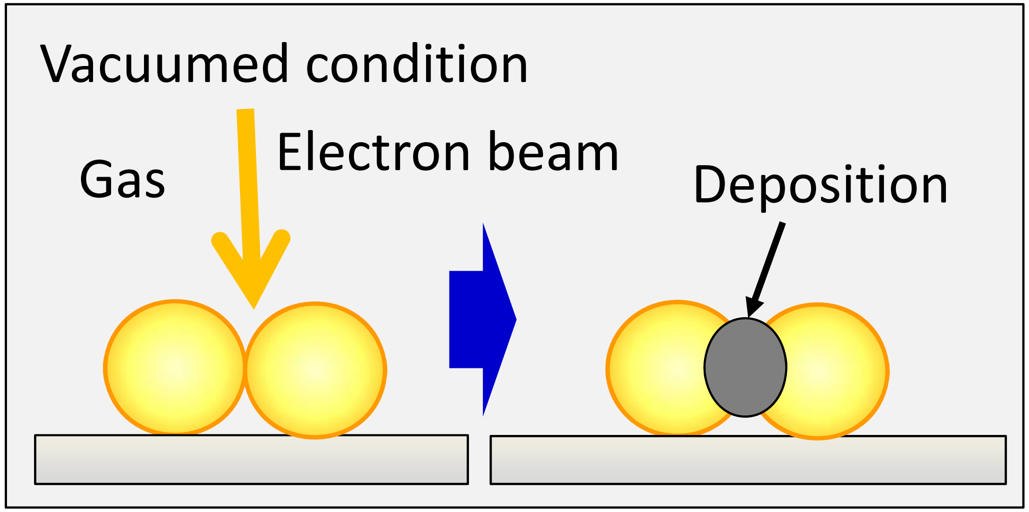


Force is measured by image processing.

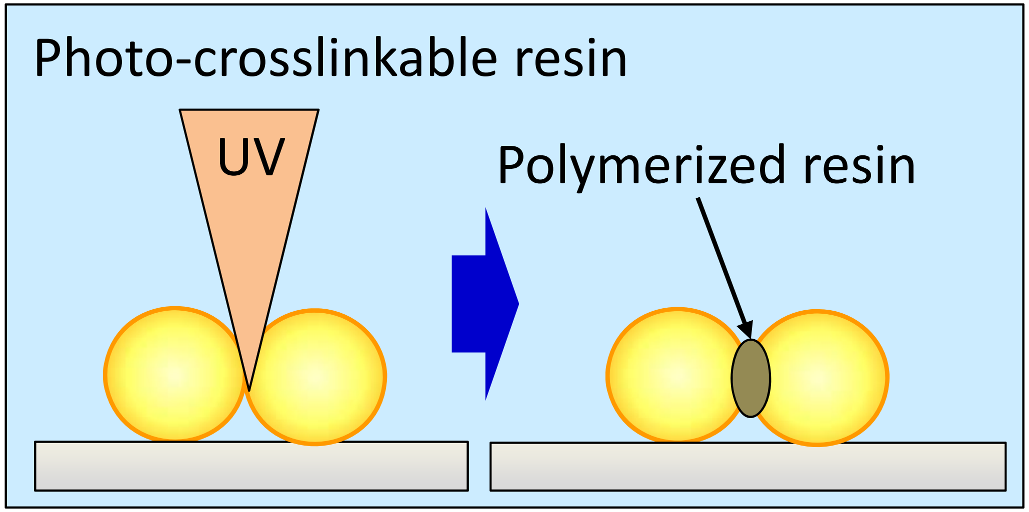
F. Arai et. al., *ICRA2009*, 2009.

Micro-Nano Assembly: Connection

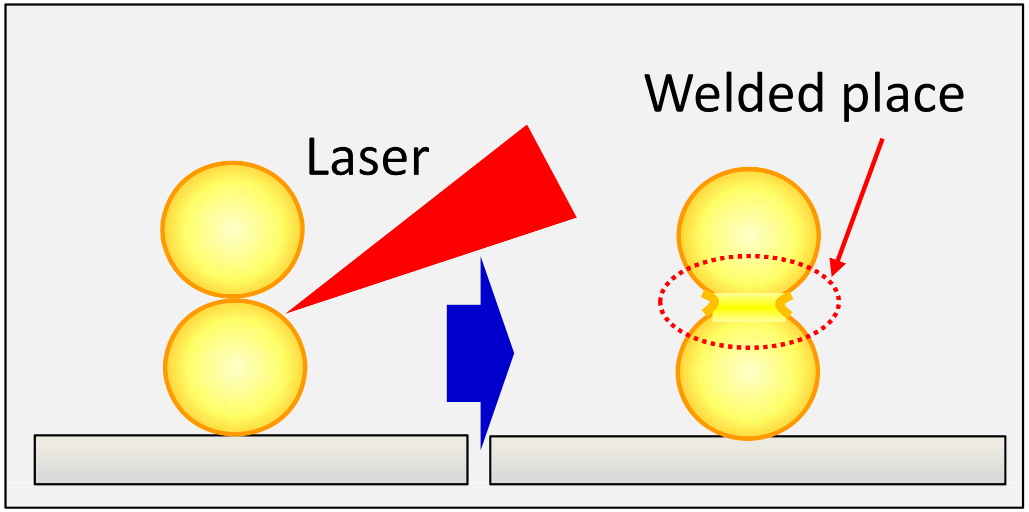
(a) Deposition method



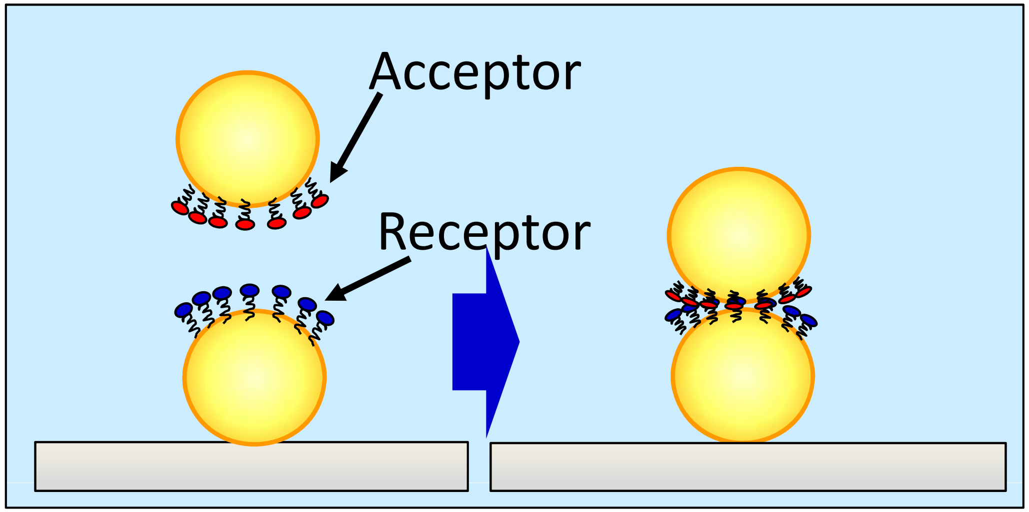
(b) Local photopolymerization



(c) Laser ablation

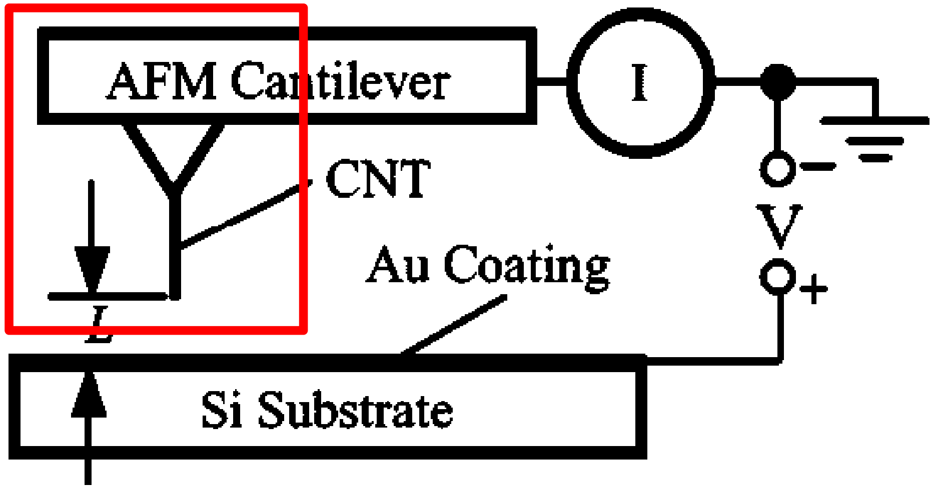


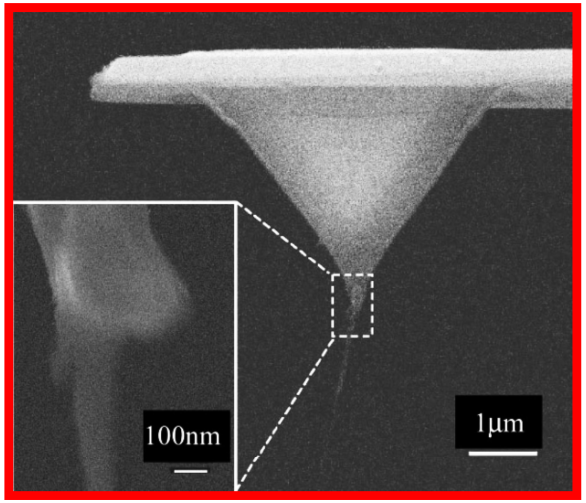
(d) Chemical bonding



Connection: Electron Beam Induced Depositio

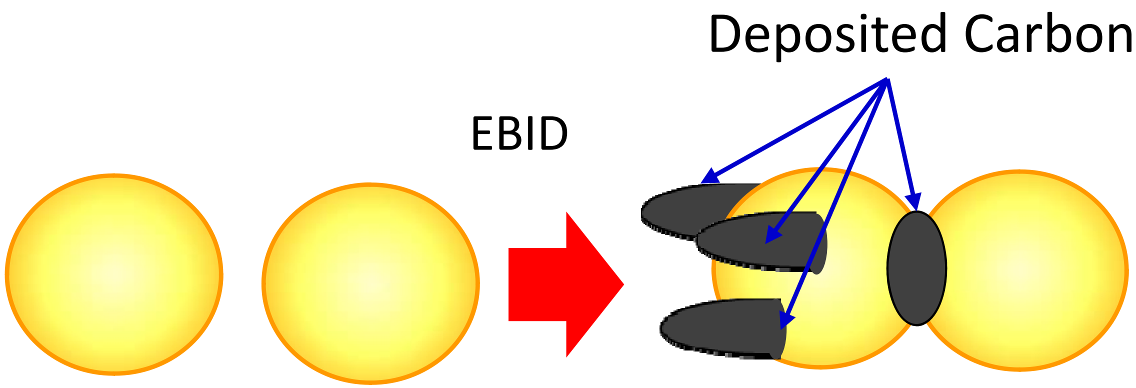
Assemble of CNT emitter by EBID

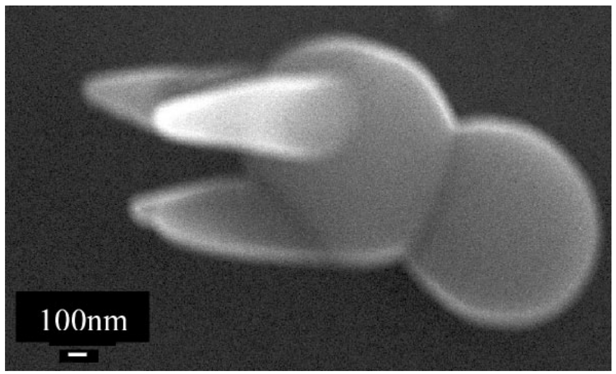




CNT connected cantirever (CNT-emitter)

Assemble of microhand by EBID



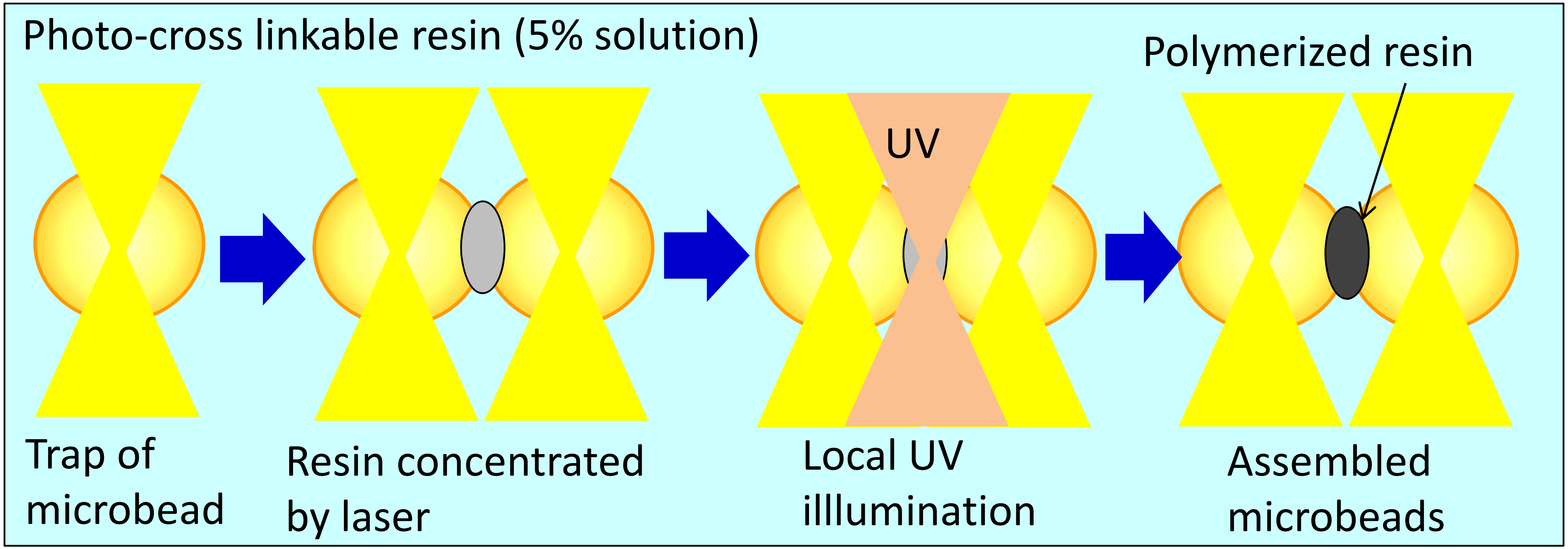


Microhand assemble by EBID

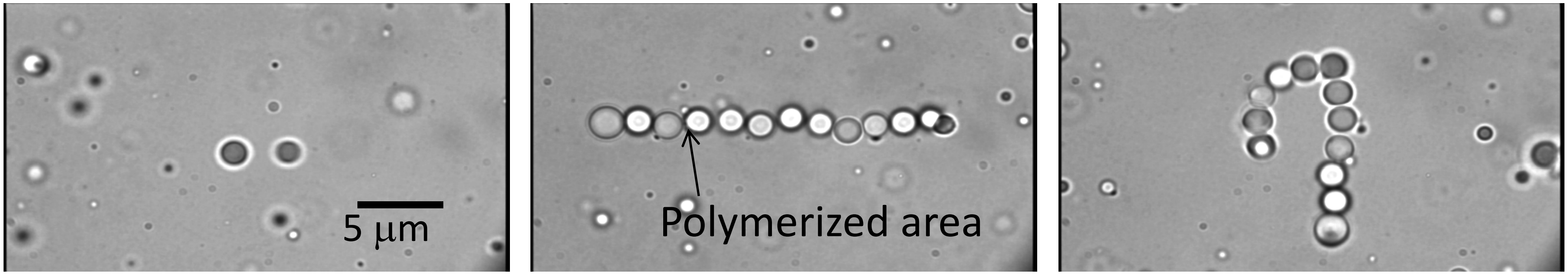
L. Dong, F. Arai, T. Fukuda, APL, 81, 1919-1921, 2002

Connection: Local Photo Polymerization

<u>In-situ assembly by local photo polymerization</u>



<u>Assembly of rope-like microtool</u>



H. Maruyama, F. Arai, T. Fukuda, JRM, 17, 335-341, 2005

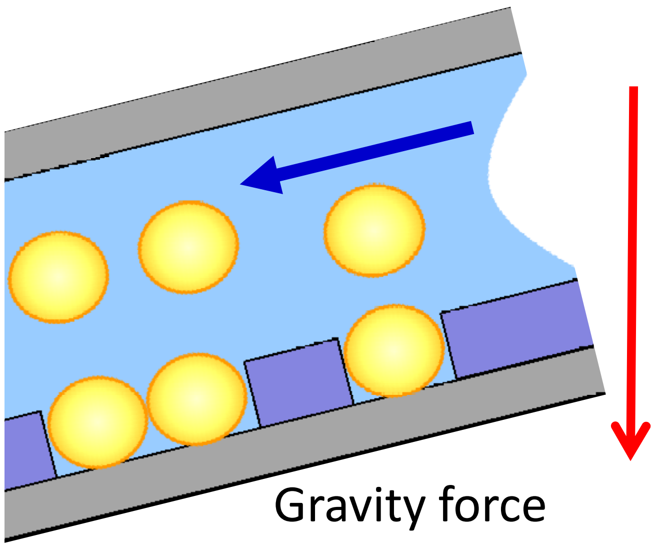
Micro-Nano Assembly: Self-assembly

Self-assembly: Nanofabrication technique that involve aggregation of colloidal particles into final desired structure.

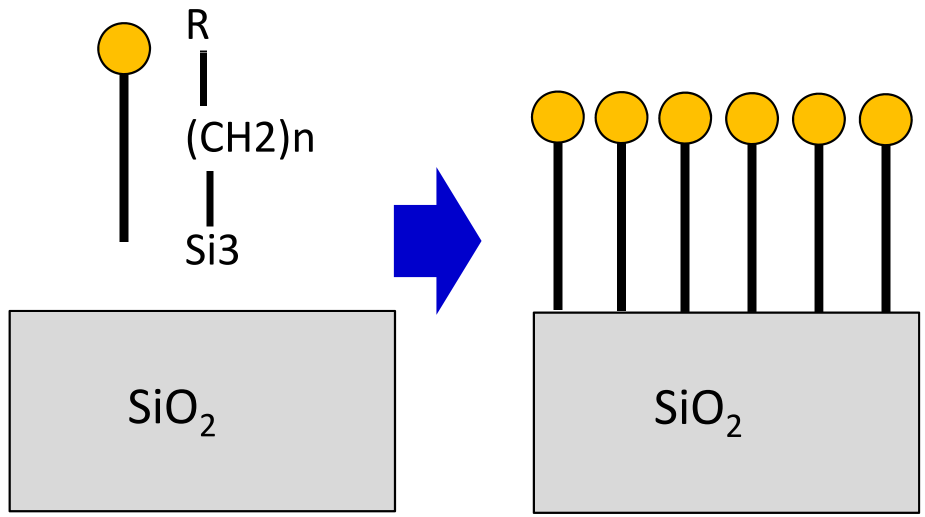
G.M. Whitesides, 2002

Classification of self-assembly

1. Physical assembly



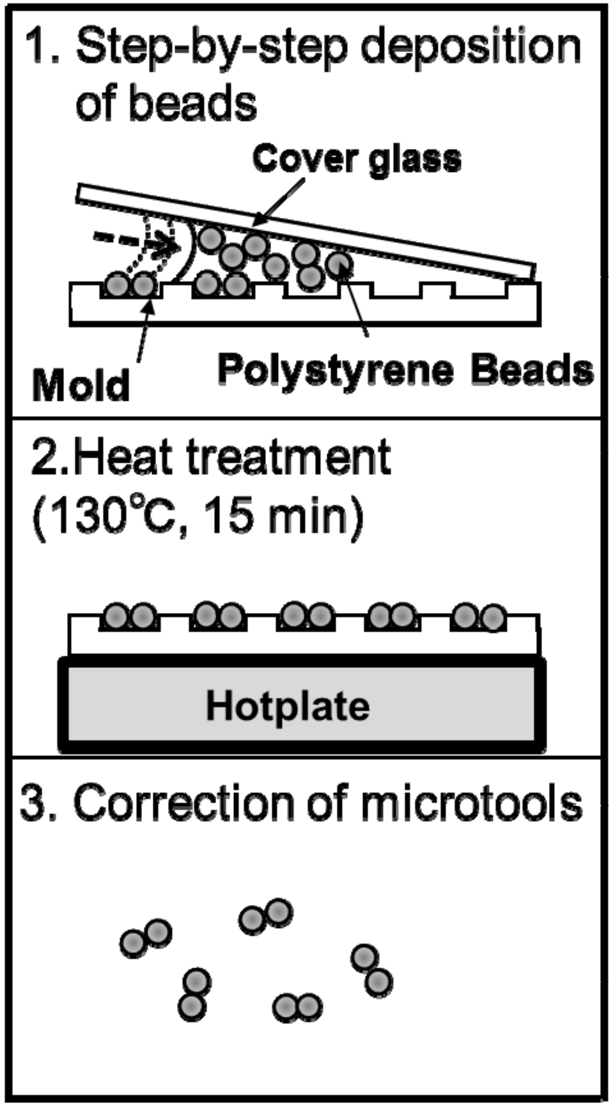
2. Chemical assembly



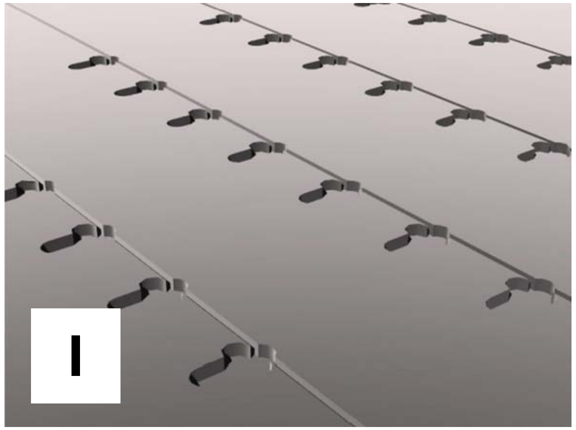
Self-assembled monolayer

Physical self-assembly with Template

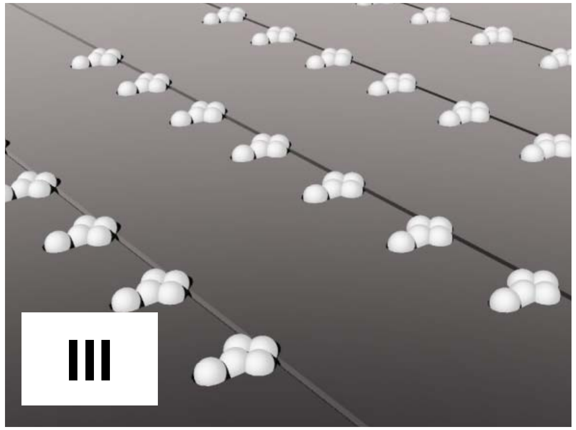
Assemble process by template-based self-assembly



I. Mold fabrication

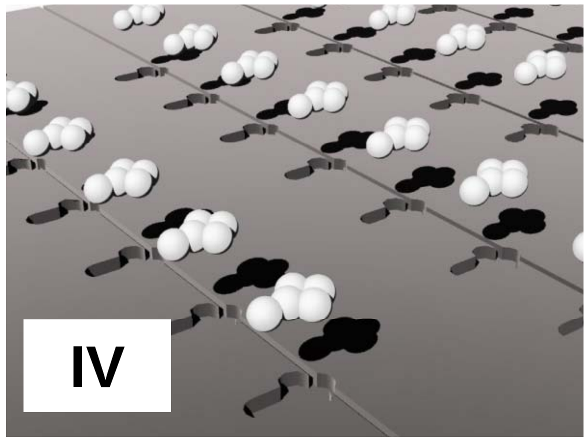


III. Bead patterning



II. Bead injection

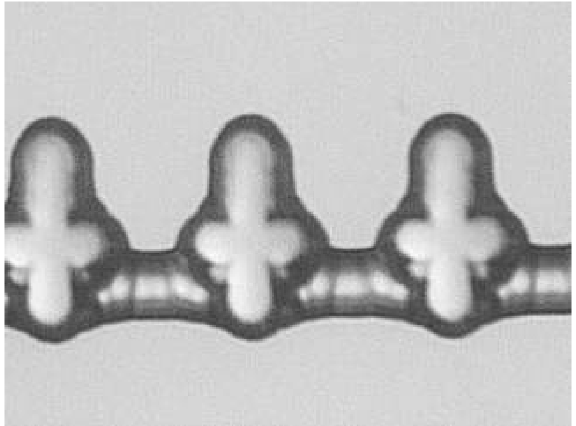
III. Heat connection



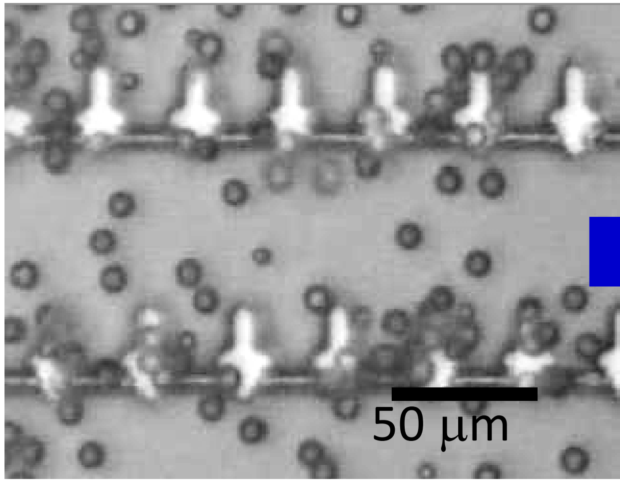
H. Maruyama, et. al., JRM, 22, pp.356-362, 2010.

Assemble results: Step-by-step deposition of beads

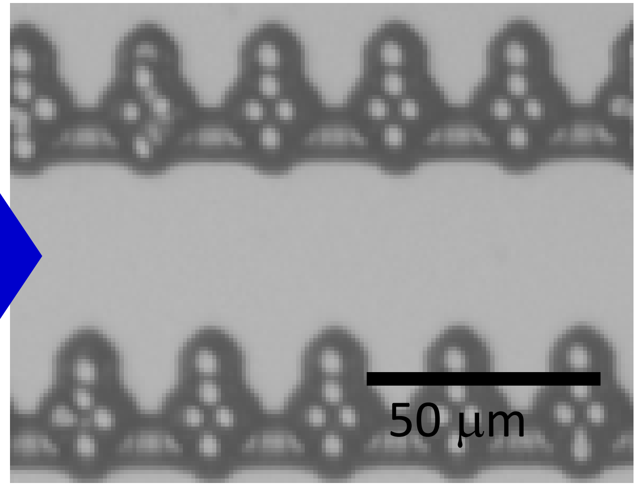
<u>Assembly of cross-shape microtool</u>



Template (Si)



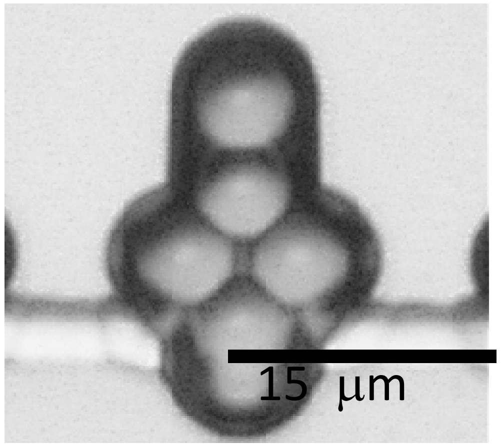
Bead injection



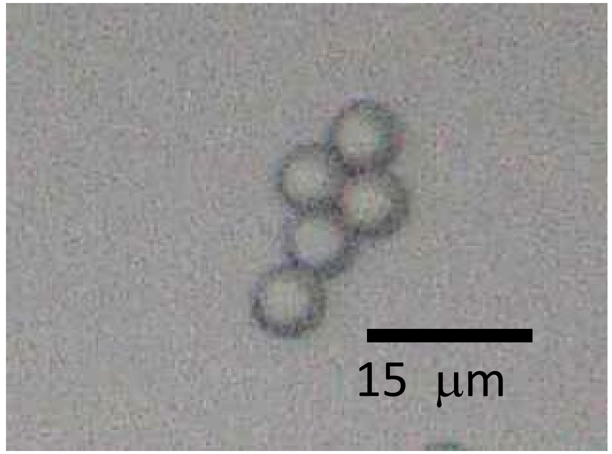
Patterned beads

<u>Enployed forces:</u>

1. Gravity force
   Bead injection into template
2. Liquid bridge force
   Alignment of bead inside template



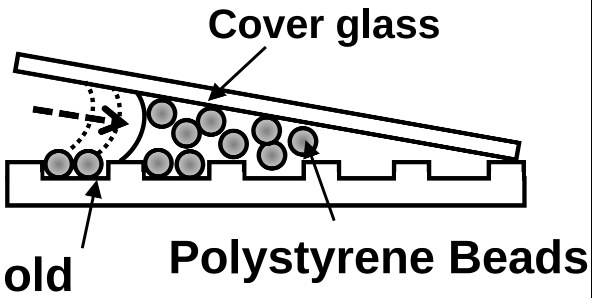
After Heat connection



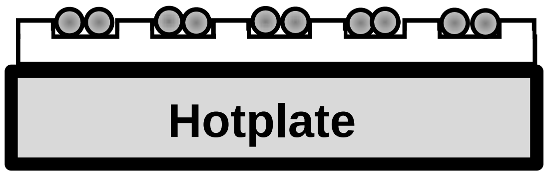
Released tool

Assemble results: Connection by heat treatment

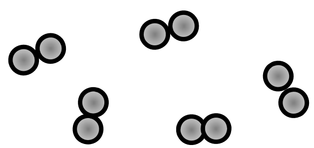
1. Step-by-step deposition of beads

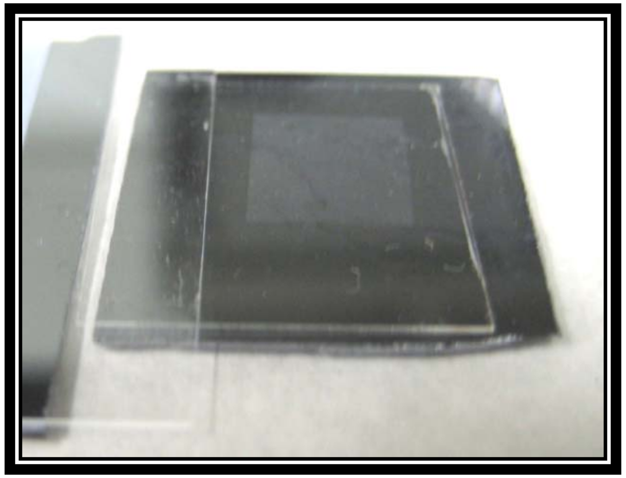


2.Heat treatment (130℃, 15 min)



3. Correction of microtools

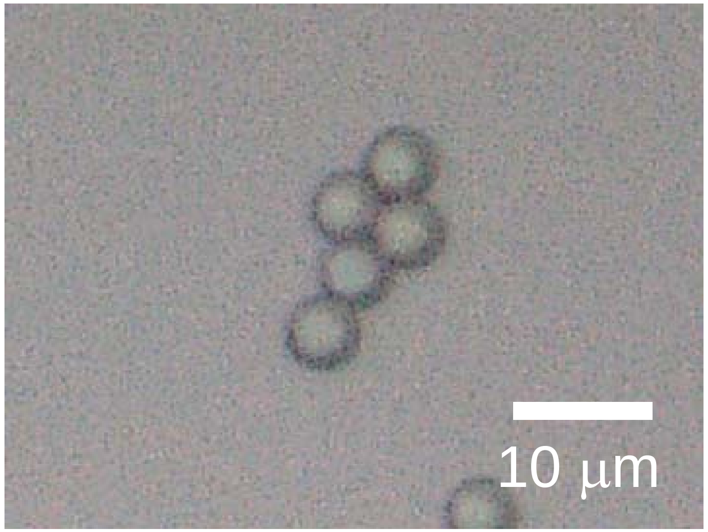


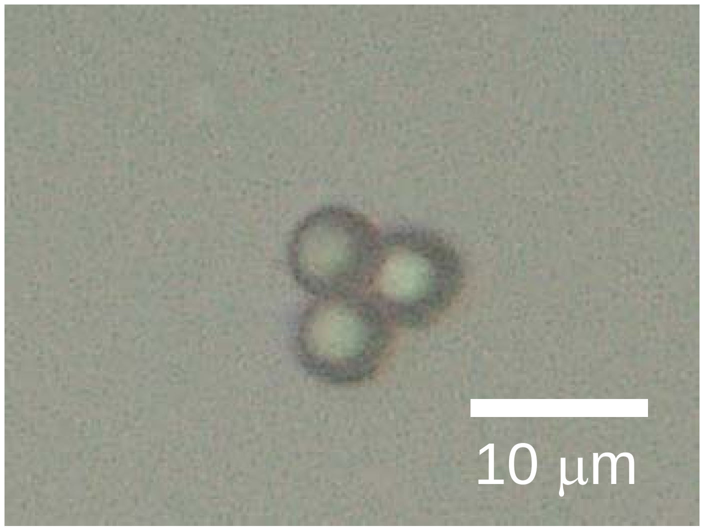


Remove from mold after heat treatment

Cross shape microtools

Triangle shape microtool





Summary

Conclusion:

Interaction force is most important parameters for micro-nano assembly process such as manipulation, connection, and self-assembly.

Self-assembly is promising technique due to its low cost and the ability of to produce structures from micro to nano scales

Future direction of micro-nano assembly:

1. Fusion of top down and bottom up approaches
2. Molecular self-assembly

    Requirement of precious molecular design

References

1. Naoki Inomata, Takahiro Kato and Fumihito Arai, "Evaluation of Thermal Conduction of Single Carbon Nanotube by Local Heating in Air", 2009 9th IEEE Conference on Nanotechnology, July 26-30, Italy (2009) pp. 112-115.

2. F. Arai, K. Yoshikawa, T. Sakami, and T. Fukuda, "Synchronized laser micromanipulation of multiple targets along each trajectory by single laser," Applied Physics Letters, 85, 4301-4303 (2004).

3. Fumihito Arai, Kazuhisa Onda, Ryo Iitsuka, and Hisataka Maruyama, "Multi-beam Laser Micromanipulation of Microtool by Integrated Optical Tweezers," Proc. of ICRA2009, pp. 1832-1837, 2009.

4. Lixin Dong, Fumihito Arai, and Toshio Fukuda, "Electron-beam-induced deposition with carbon nanotube emitters," Appl. Phys. Lett., 81, pp. 1919-1921

5. H. Maruyama, F. Arai, T. Fukuda, "Microfabrication and Laser Manipulation of Functional Microtool using In-Situ photofabrication," Journal of Robotics and Mechatronics, Vol. 17, No.3, (2005), pp.335-341.

6. H. Maruyama, R. Iitsuka, K. Onda, F. Arai, "Massive ParallelAssembly of Microbeadsfor Fabrication of Microtools Having Spherical Structure and Powerful Manipulation by Optical Tweezers," Journal of Robotics and Mechatronics, Vol. 22, no. 3, (2010), pp.356-362.