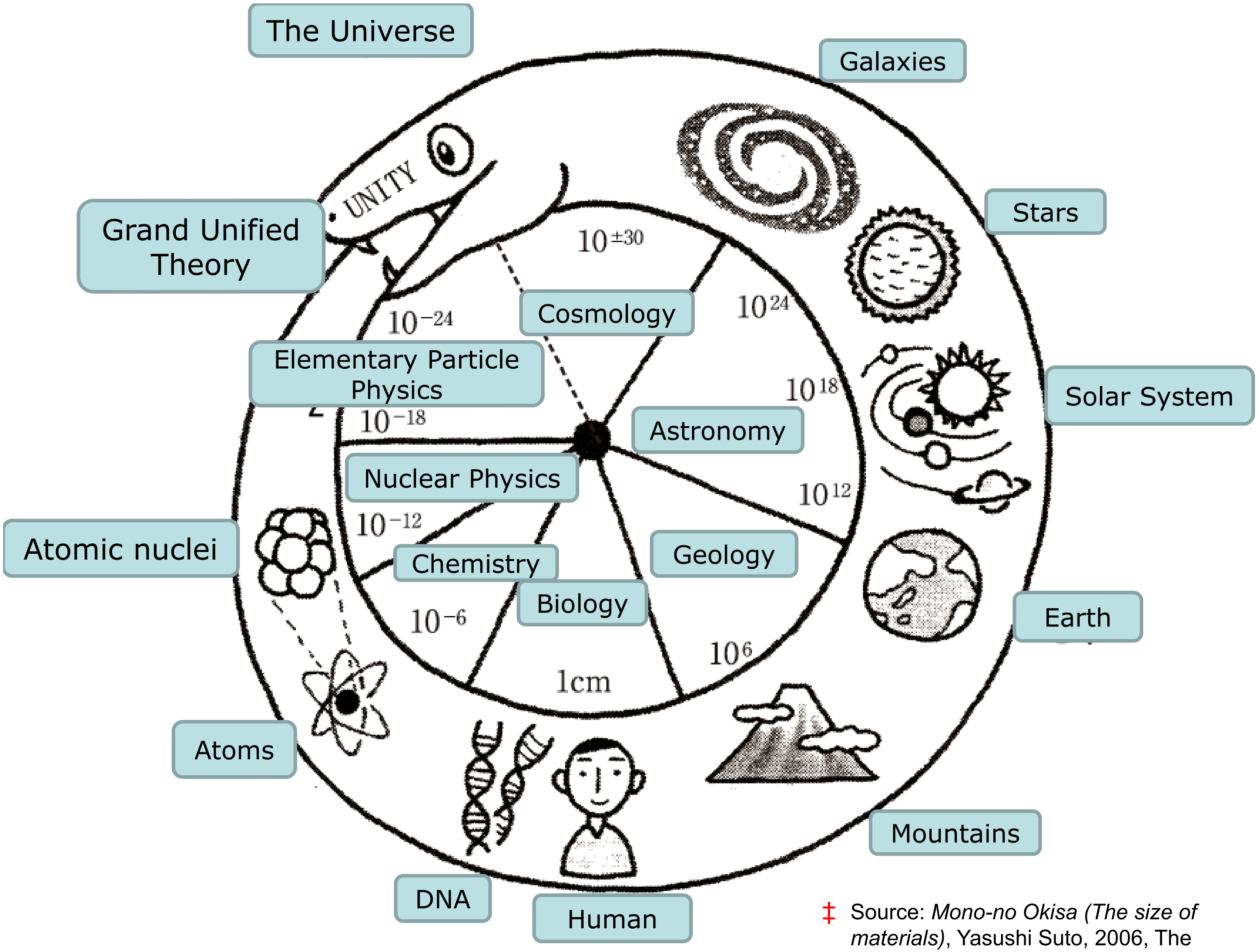
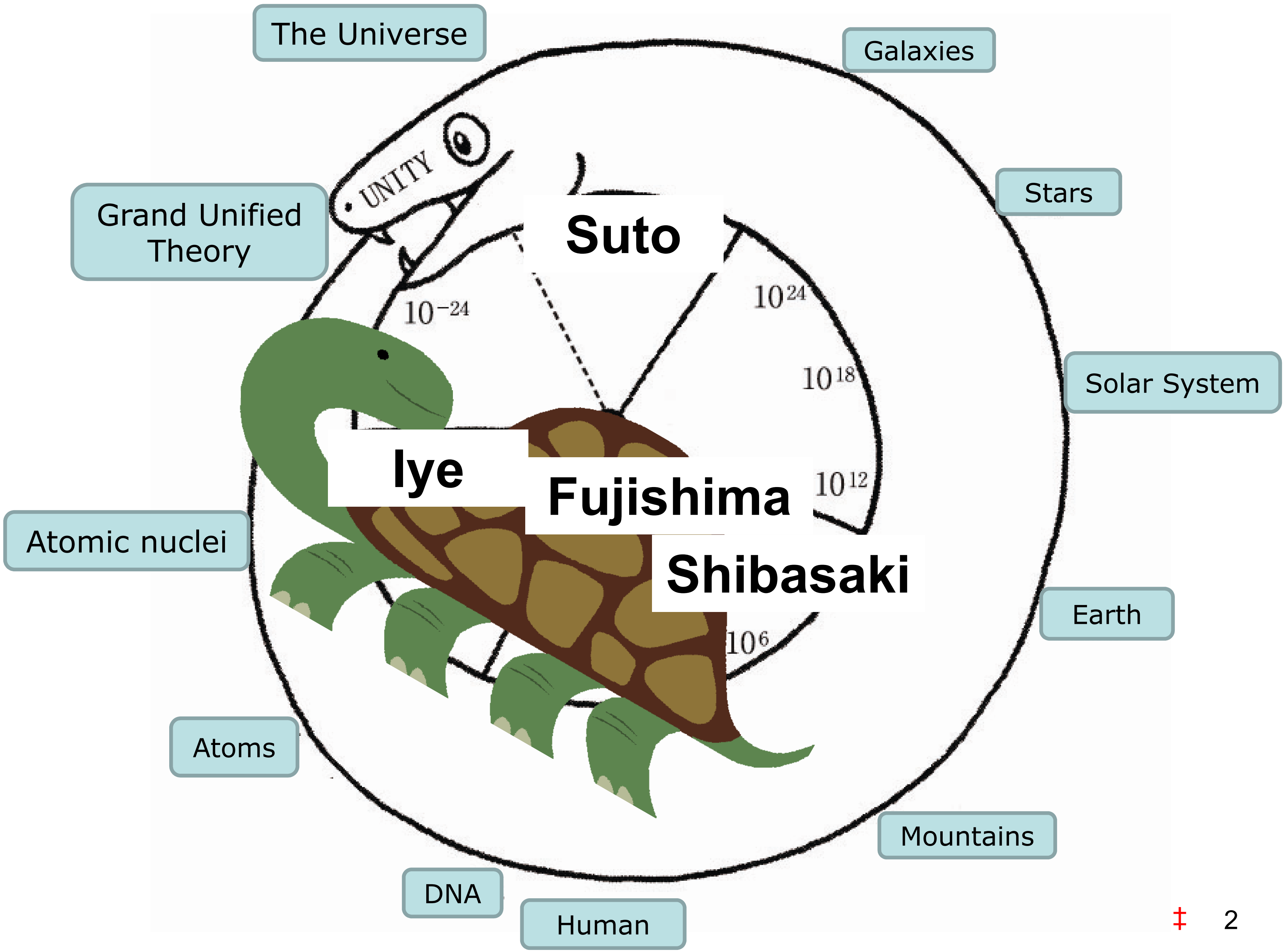


‡ Source: *Mono-no Okisa (The size of materials)*, Yasushi Suto, 2006, The University of Tokyo Press


The Universe
Galaxies
Stars
Solar System
Earth
Mountains
Human
DNA
Atoms
Atomic nuclei
Grand Unified Theory
UNITY
10^{-24}
10^{24}
10^{18}
10^{12}
10^{6}
Suto
Iye
Fujishima
Shibasaki

Global Focus on Knowledge

The Production and Aplication of Matter

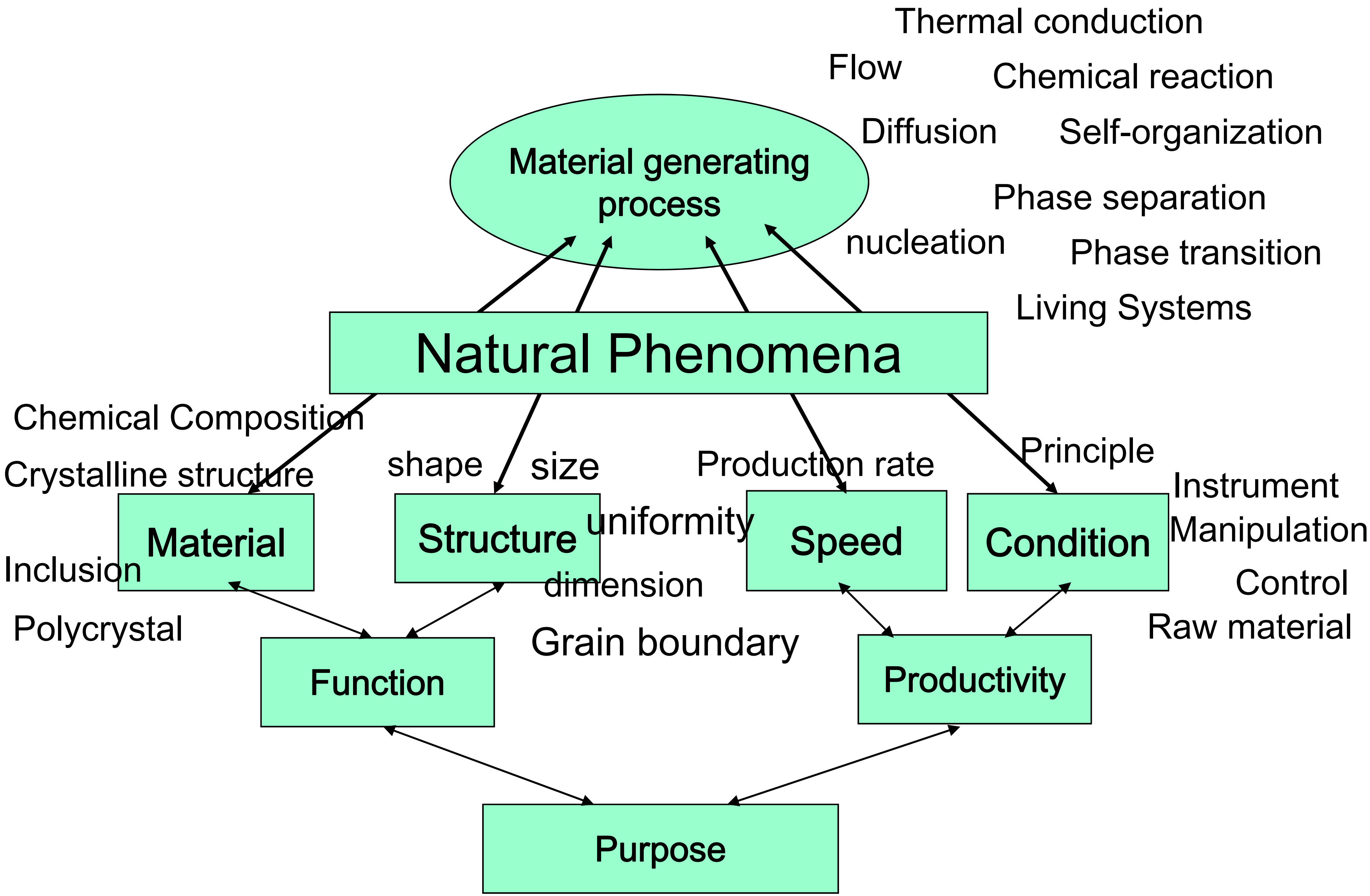
Lecture 2: Conjugation (devices)

Semiconductors（Si,GaAs)

Soft matters

Hiroshi Komiyama

(the University of Tokyo)


Thermal conduction
Flow
Chemical reaction
Diffusion
Self-organization
Material generating process
Phase separation
nucleation
Phase transition
Living Systems
Natural Phenomena
Chemical Composition
Crystalline structure
shape
size
Production rate
Principle
Instrument
Manipulation
Material
Structure
uniformity
Speed
Condition
Inclusion
dimension
Control
Polycrystal
Grain boundary
Raw material
Function
Productivity
Purpose

Introduction

Semiconductors: semiconductor devices,
Optical Fibers, photocatalytic reactor

Composition, Structure（Form and size in particular)
Speed

Phenomena: Flow, Diffusion, Thermal Conduction

Soft matters： Liquid Crystal Displays,
Color films,Color Filters, Molecular Sensors
Substance（Molecular structure,Molecular Design）
Structure (Form)
Speed（multilayer coating/ Inkjet Prints)･Conditions
Phenomena: Self-Organizations, Chemical Reactions,
Flows (driven by surface tension)

II-1. Inorganic Materials

Semiconductor Devices , Optical Fibers,
Chemical Reactors

Composition, Structure（Size and Form）, Speed

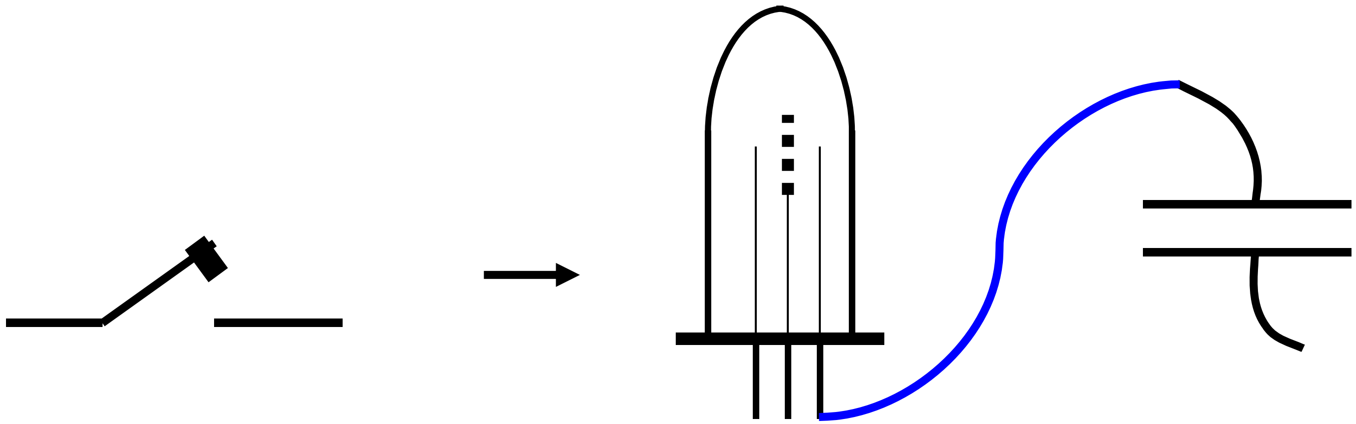
Phenomena: Flow, Diffusion, Thermal Conduction

Semiconductors

Electric conductance dramatically changes (10^10 times) due to impurities, optical irradiations, electric fields

Metals: 10^{-6} ～10^{-4} Ω-cm
Semiconductors: 10^{-3}～10^{8} Ω-cm
Insulators: 10^{10} Ω-cm～

Memory devices composed of switches and binary cells

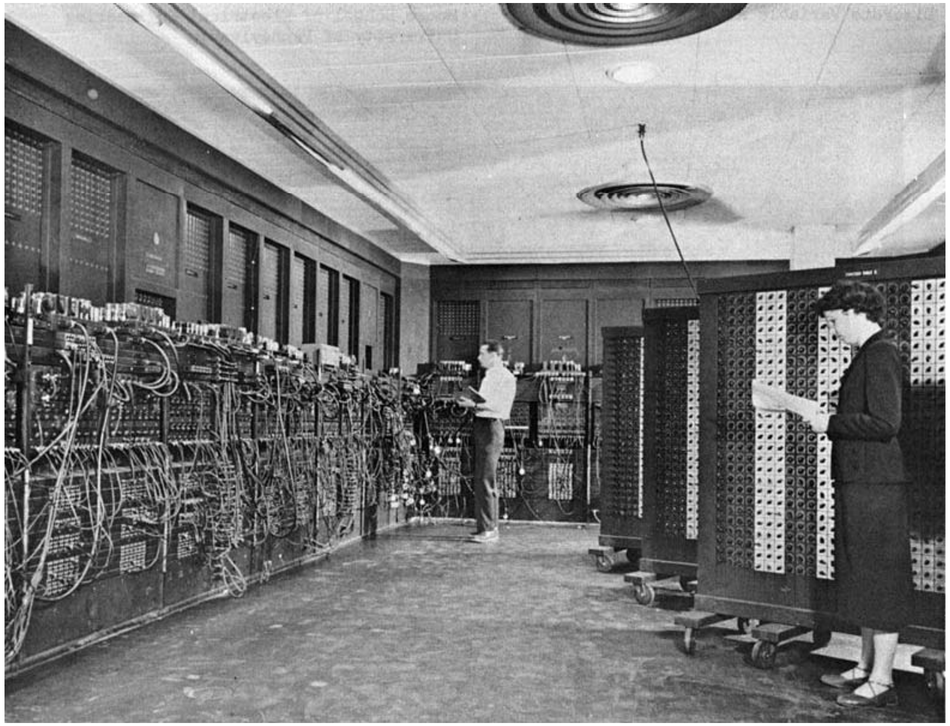


Telegrams and computations using mechanical switches

Vacuum tube Capacitor

$Q = CV$

Vacuum Tube Computers



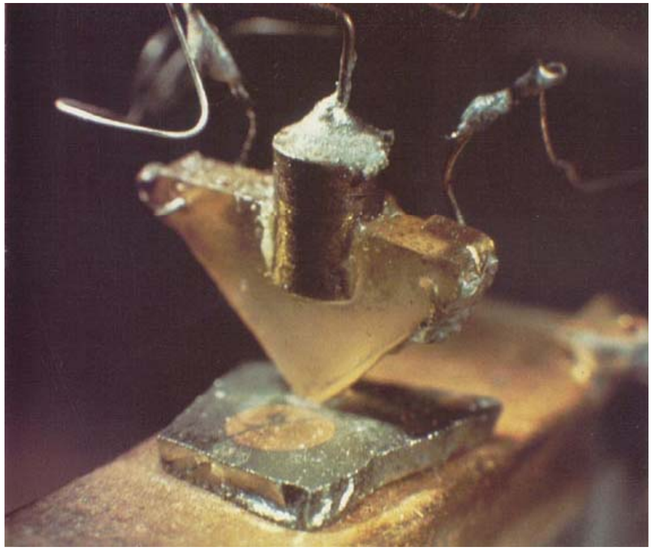
Source:
Wikipedia

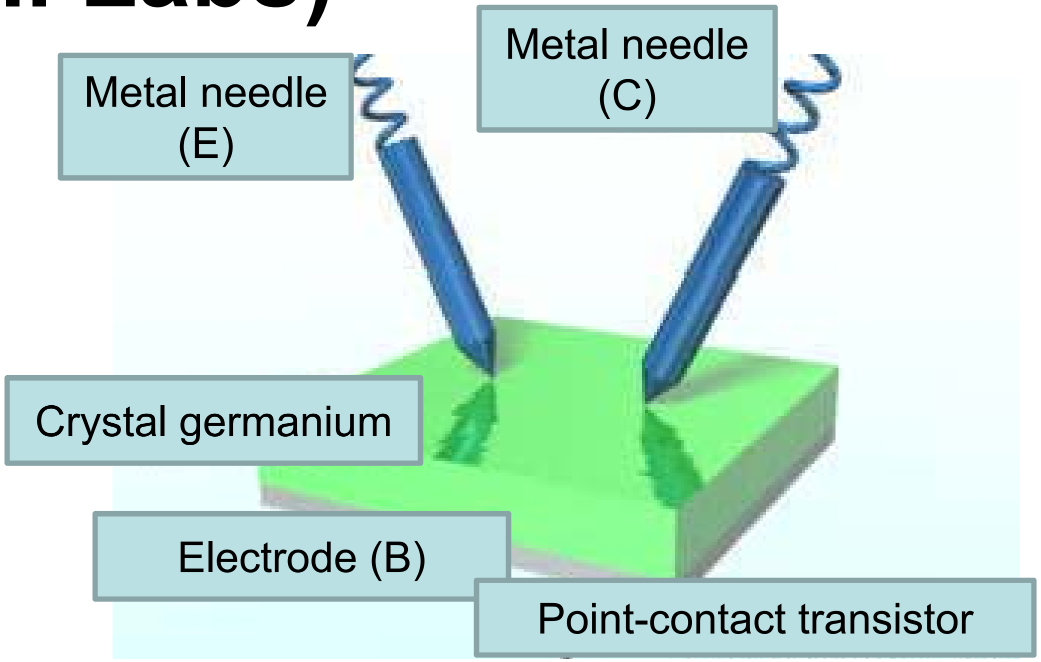
1946：ENIAC（Electronic Numerical Integrator and Computer）
The world's first electric Computer equipped with 18,000 vacuum tubes

It took three seconds to compute a ten-digit ballistic trajectory.
ballistic computing

●power consumption: 140kW
●life span: several hours

1947 invention of the transistor (Bell Labs)





Dec 16, 1947:

operation check of the first transistor

Low energy consumption

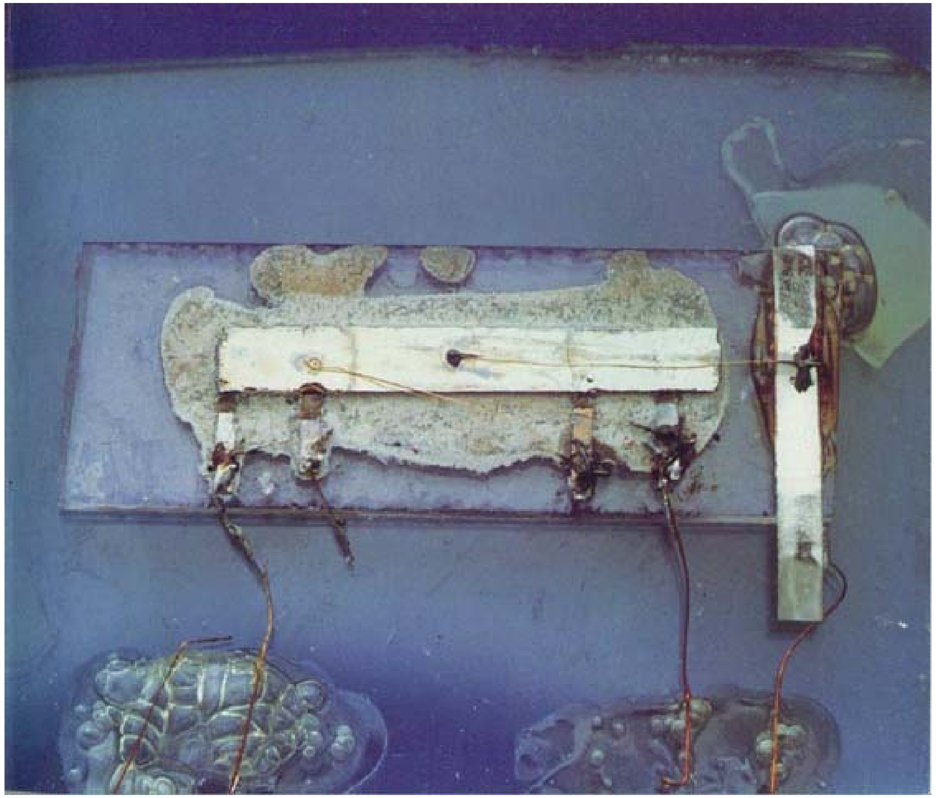
High credibility

Long lifetime

W.Brattain, J.Bardeen, W.Shockley
Nobel Prize in Physics (1956)

Integration: From Transistors to ICs

- Utilizations of transistors
  - Radar (military purposes)
  - Telephone exchange operation by AT&T (mechanical cable type)
  - Applications to radio receivers (SONY)
  - Large scale computers (IBM)
- transistors were gradually replaced by the ICs



‡ Invented by Dr. Jack Kilby (Texas Instruments Inc.)
Nobel Prize in Physics (2000)

Advantages of Integration

① High work-rate thanks to miniaturization of transistors

a transistor that is 1/k times the size of the original works k ～k^2 times faster

② Integration of different function enables the realization of multifunction ICs

mixed loading of CPU, graphic ICs, and Memory chips

→realization of a one-chip PC etc.

③ Economic efficiency：decrease of prices per bit

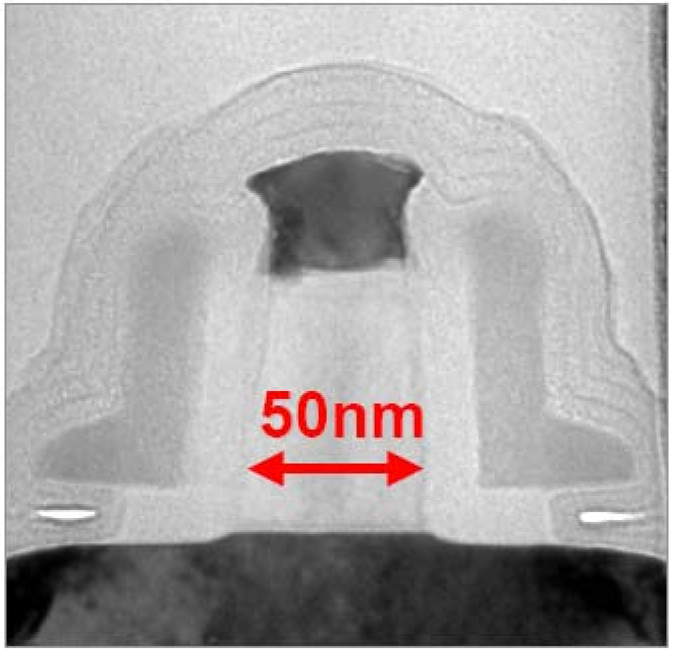
a factory that costs ¥200,000,000,000 produces 10,000,000 wafers every year

→¥200 /chip, ¥60,000 /wafer

→¥600,000,000,000 sales /year

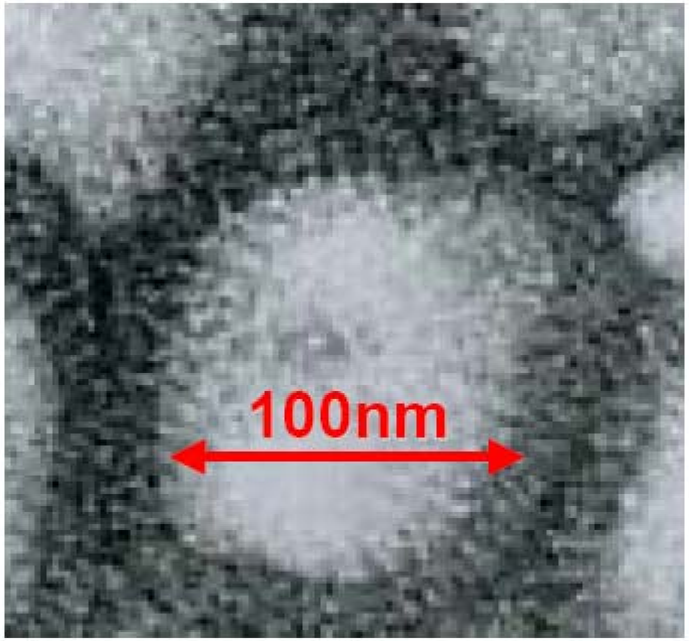
Already smaller than a Virus

45nm process at present



Transistor for 90nm process

‡ Source: Intel



Influenza virus

‡ Source: CDC

(Dr. Erskine Palmer, Centers for Disease Control and Prevention Public Health Image Library)

History of Semiconductors

- Vacuum tubes and Solid elements coexisted
- Invention of Transistors (1947)
- Germanium（1950s）
- Silicon, IC（1960s）Integrated Circuit
- ULSI（1970s～）　Ultra Large IC
- Semiconductors composed of many kinds of chemical compounds coexist
- GSI,（21st Century)　　Giga-scale Integration
- ???Quantum elements???

Driven by the Technology Advancement

Anyway, the surface is inevitably oxidized

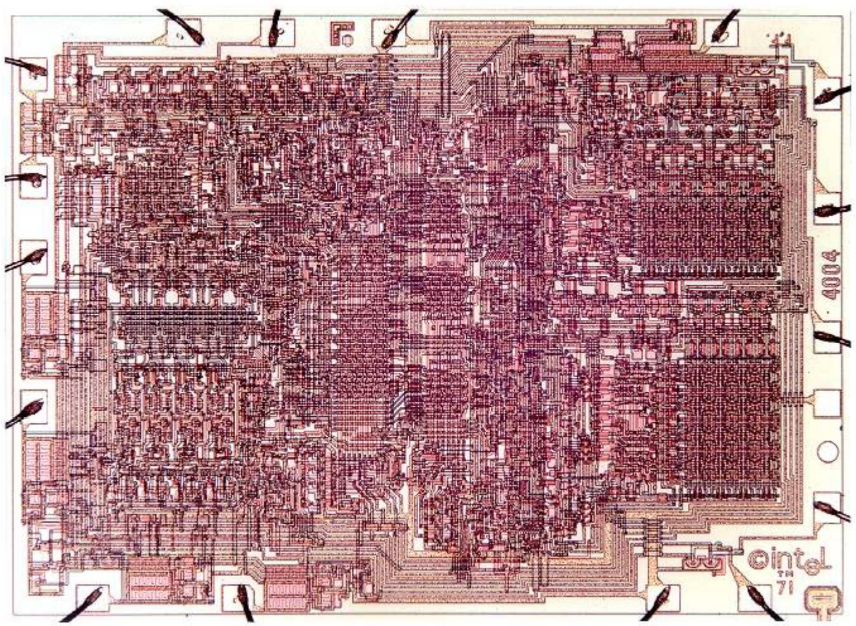
Si oxidized film is of good quality
Ge oxidized film is unstable（water soluble）
group III-V semiconductors（e.g. GaAs）are hard to control

The Task is Conquerable

group III-V Semiconductors（e.g. GaAs）is luminous
Silicon will be luminous
technology of combinational use
nanodot

the first CPU in the world developed by Intel (1971)

‡

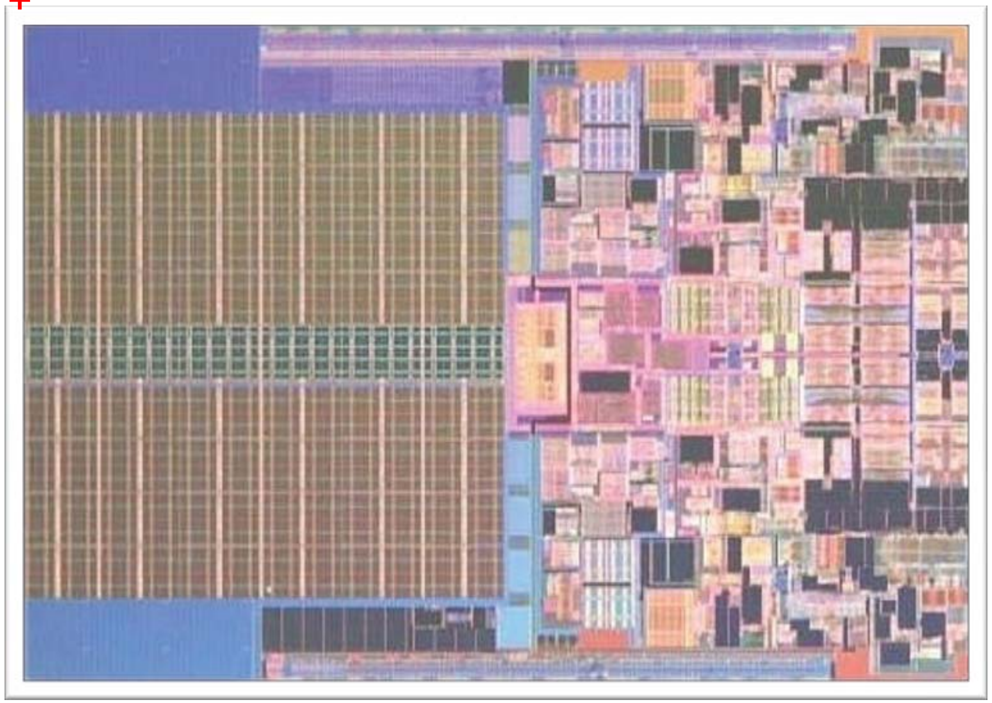


Developed upon a request from Busicom (a Japanese Company),as a calculator

4004（CPU）
3mm×4mm、2237 transistors

A processor developed by Intel (2008)

‡

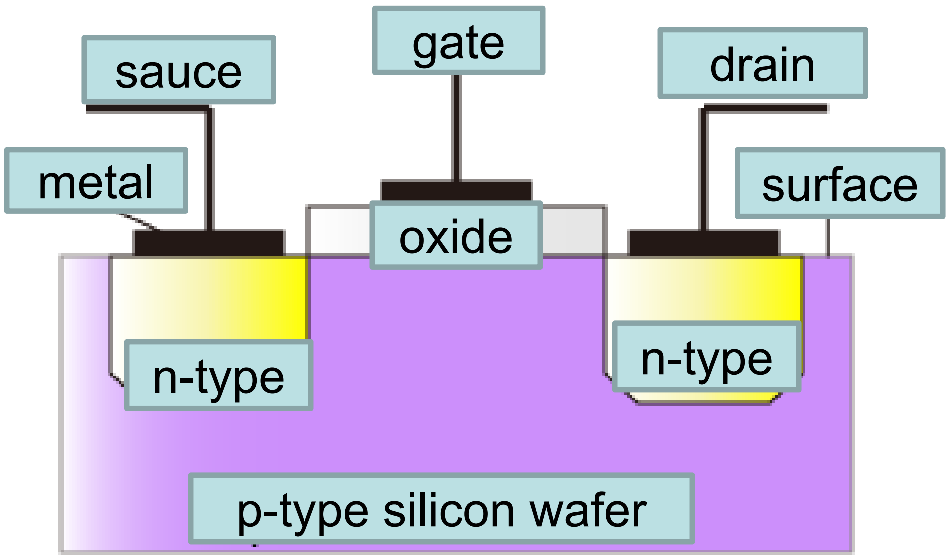


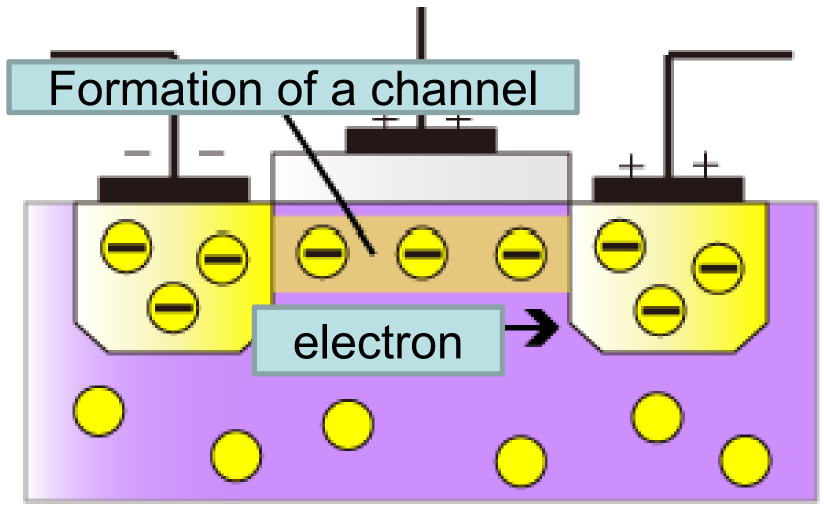
45nm process
Including 410,000,000 transistors

(Dr.Masatoshi Shima is one of the developers)

MOS transistor

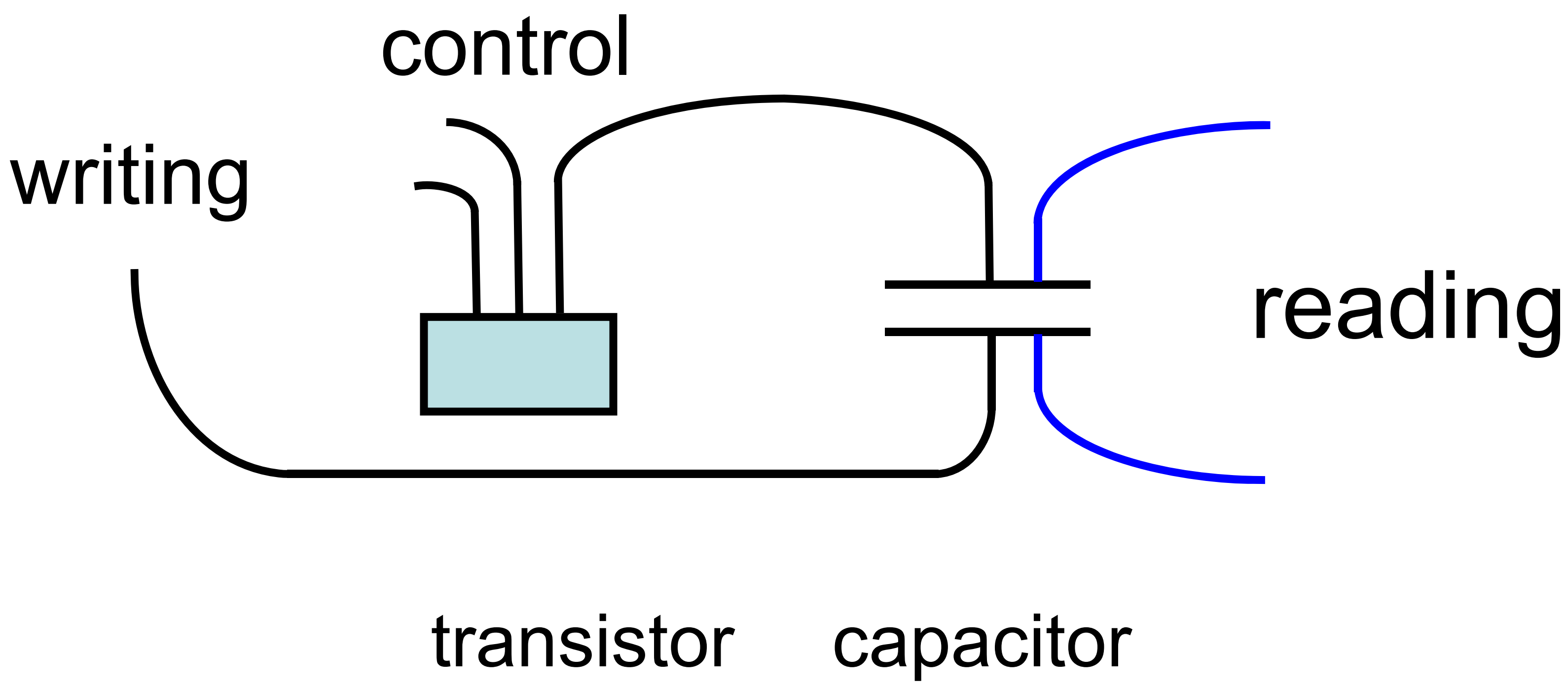
- **M**etal-**O**xide-**S**emiconductor Structure
- on/off switching the electric current (sauce to drain) with the voltage at the gate





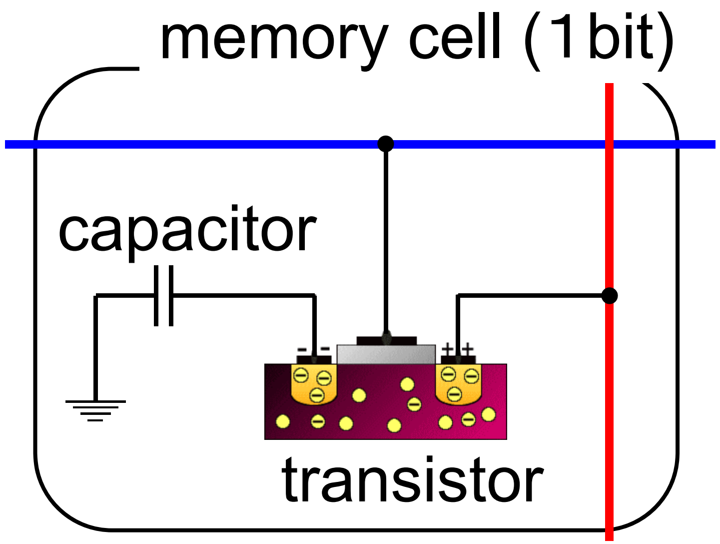
‡Provided by Prof. Shimogaki, The University of Tokyo

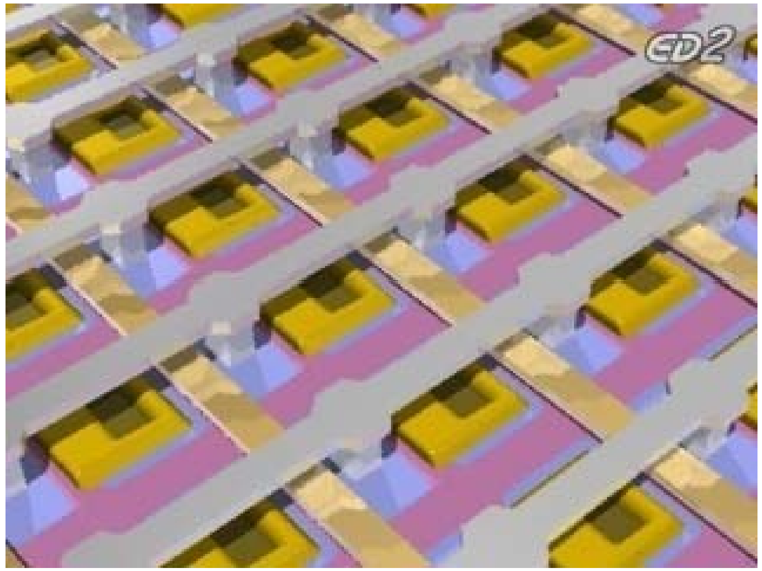
A Memory Cell is Made Up of a Control Gate and a Binary Cell

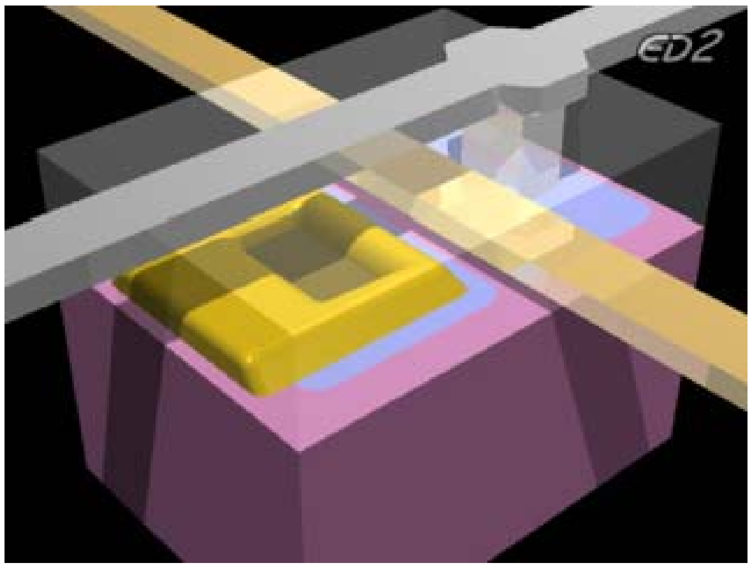


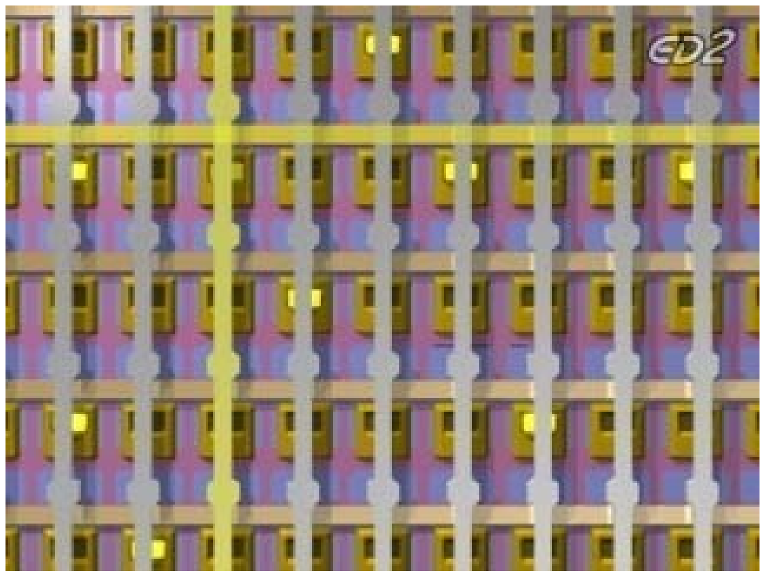
‡Provided by Prof. Shimogaki, The University of Tokyo

Structure of DRAM(dynamic random access memory)









The inevitability of nanotechnology

A memory of 10^9 bytes

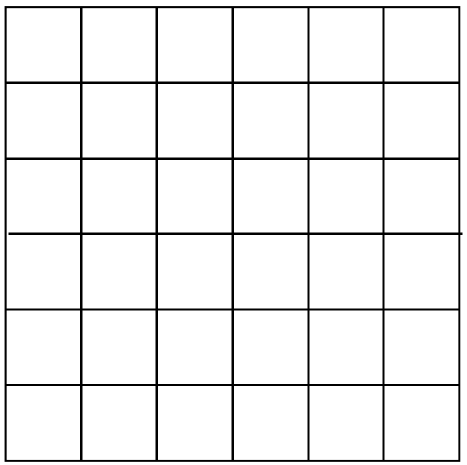
$= (3 \times 10^4) \times (3 \times 10^4)$

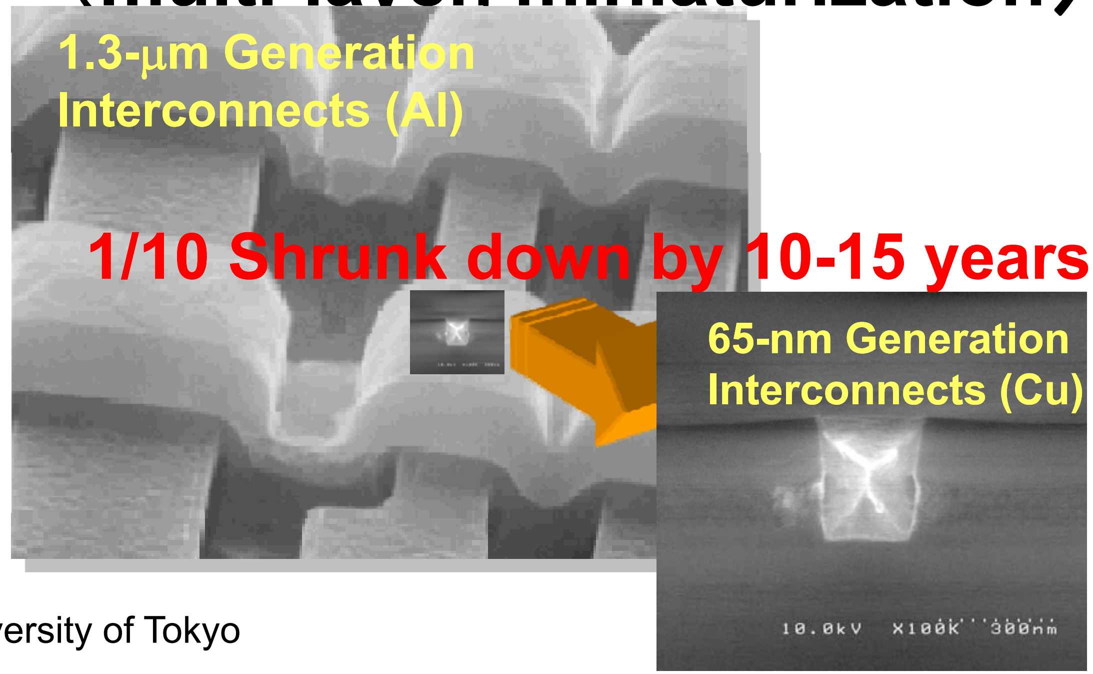
1cm × 1cm(chip)

$= 0.3\ \mu m \times 0.3\ \mu m$ (element)

Wiring gets harder

(multi-layer, miniaturization)





‡Provided by Prof. Oba, The University of Tokyo

A process for producing high purity silicon

① Reduction of SiO_2@1200℃

SiO_2 + C → Si (98% purity) + CO_2↑

② Trichlorosilane production

Si + 3HCl → $SiHCl_3$ + H_2↑

③ Distillation and purification

$SiHCl_3$（98%）→ $SiHCl_3$（99.99999999%）

④ Synthesis of pure solid Silicon through CVD process

$SiHCl_3$ + H_2 → Si（high purity）＋ 3HCl

Producing single crystal Silicon wafers（movie）

the movie here has been removed
due to a copyright issue.

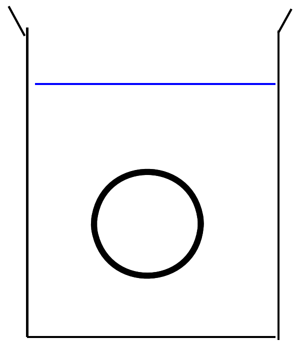
CZ（Czochralski） method:

1. Melting high-purity multi-crystal silicon at high temperature
2. Single crystal growth with seed crystal

Wafer diameter control through pull-up speed and temperature distribution

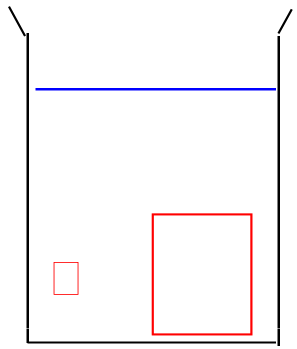
Ｑ&Ａ　What is a nucleation?

An air bubble vanishes at 90℃
→100℃ corresponds to the atmospheric pressure



The Stability

→heat generation and glueing (in vacuum)
→Ostwald ripening
→bubbles are less stable than liquid
→supersaturation (over 100℃) is necessary



Nucleation is described by the theory of statistical mechanics and thermodynamics

Common processes for microfabrication

Goal: high production rate, high spatial density, consistent quality

Pattern formation (lithography)

① Photoresist coating

② UV ray exposure and image development

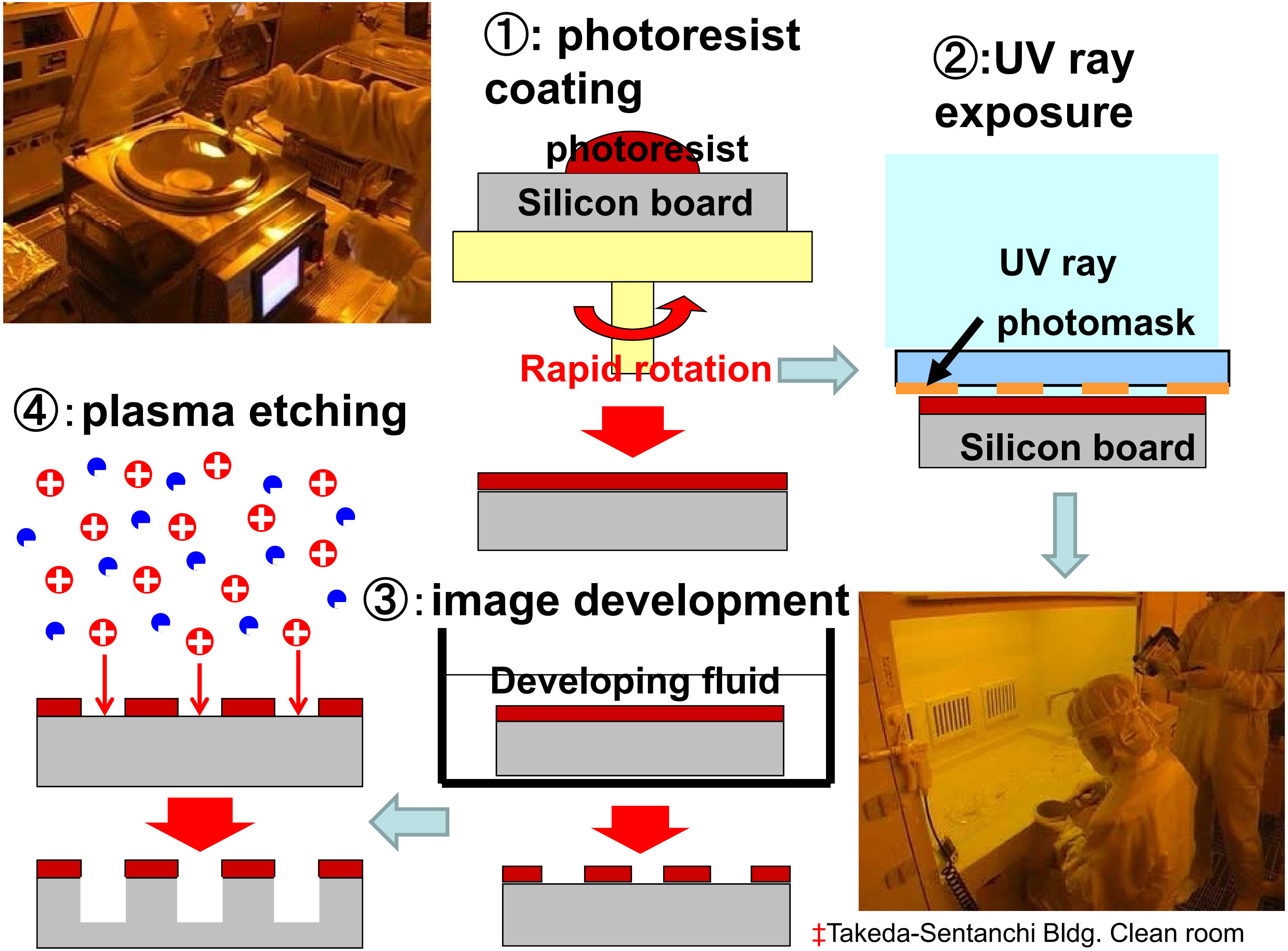
③ Plasma etching

④ Resist removal

Thin membrane producing

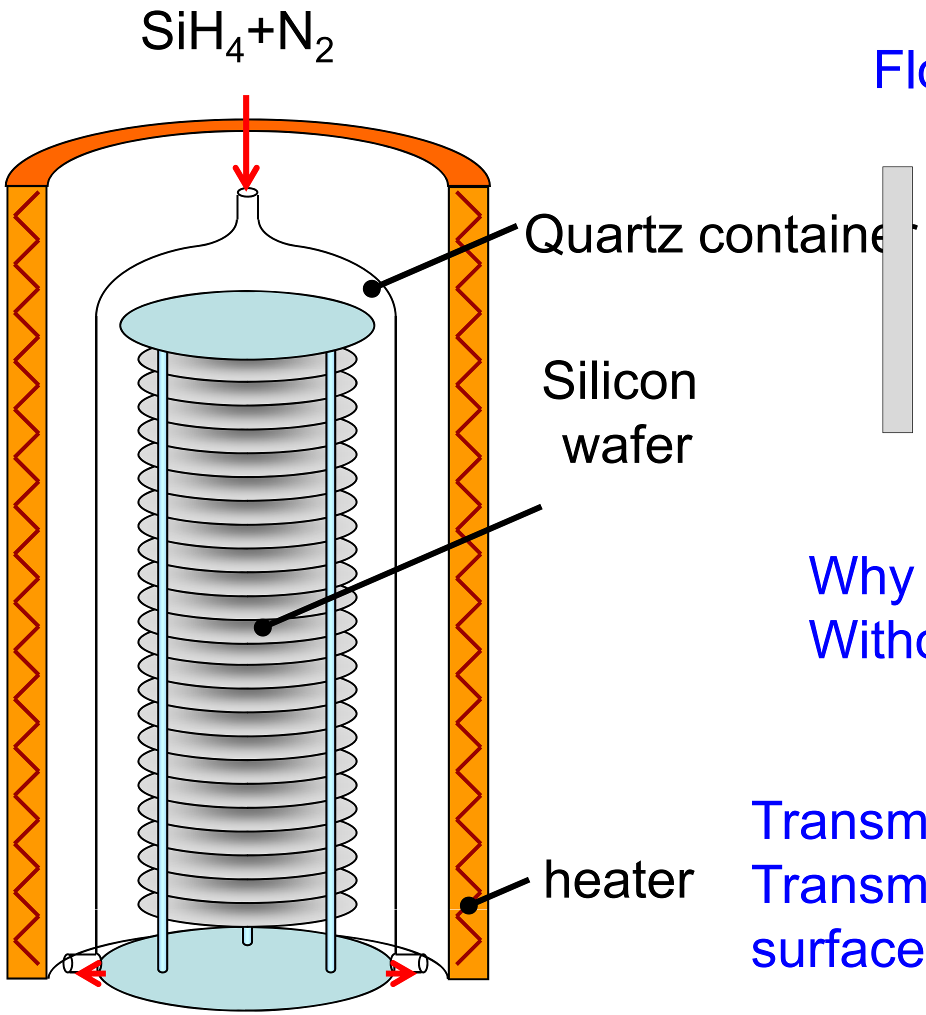
Through PVD，CVD method

Impurity doping (ions)

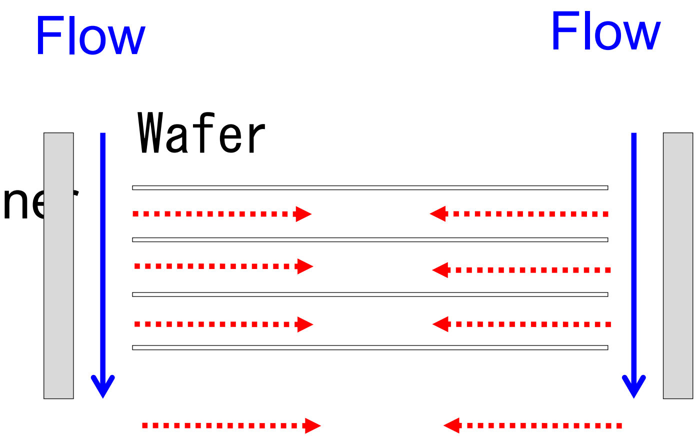


‡Takeda-Sentanchi Bldg. Clean room
(The University of Tokyo)

CVD(chemical vapor deposition) **equipment for mass-production**
Gas →Chemical Reaction→formation of membrane at the surface



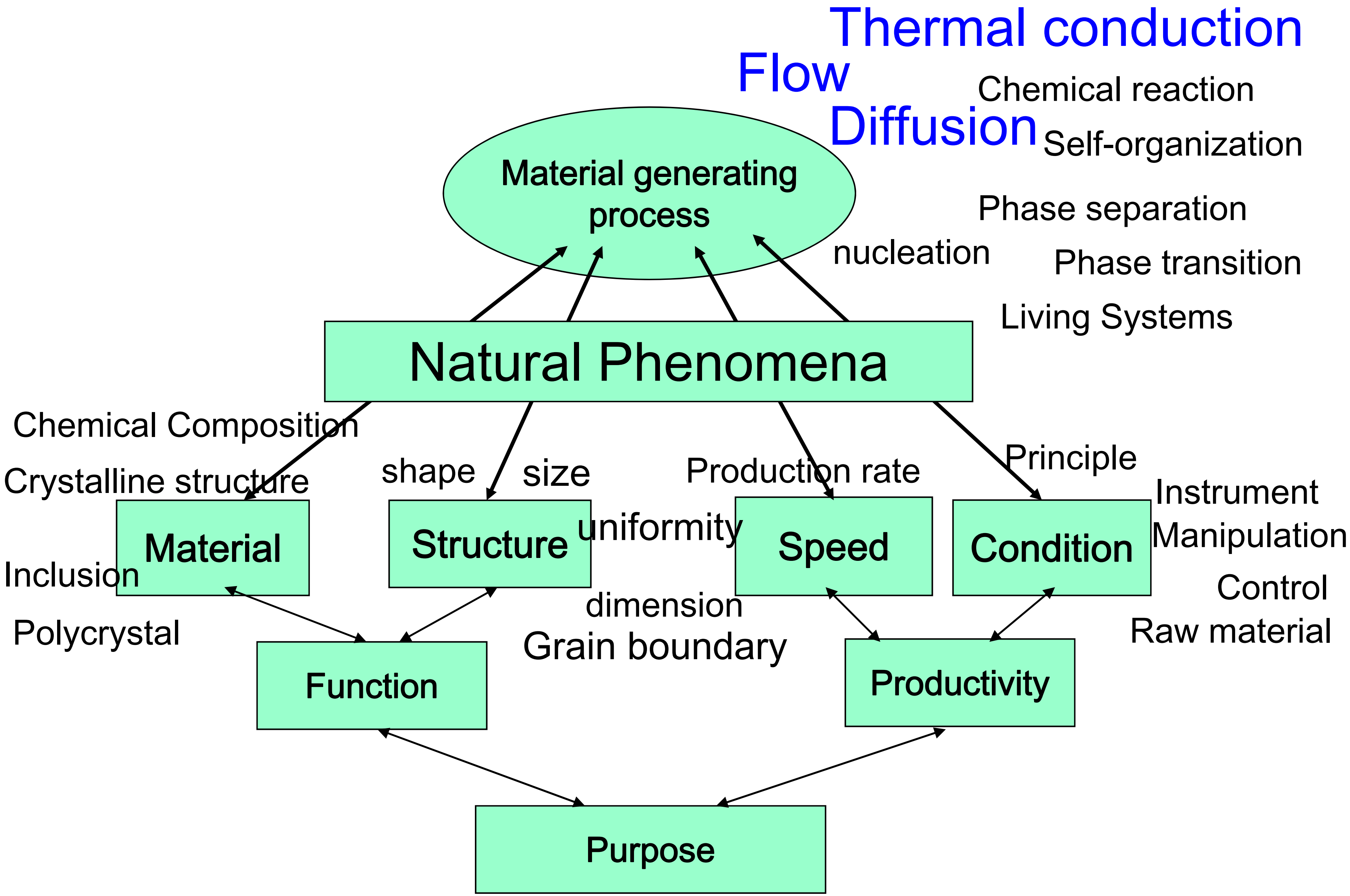
Flow and Diffusion



Why does membrane form
Without flow?

Transmission by flow (in the equipment)
Transmission by diffusion(on the wafer surface)

‡



Thermal conduction
Flow
Diffusion
Chemical reaction
Self-organization
Phase separation
nucleation
Phase transition
Living Systems
Material generating process
Natural Phenomena
Chemical Composition
Crystalline structure
Inclusion
Polycrystal
shape
size
uniformity
dimension
Grain boundary
Production rate
Principle
Instrument
Manipulation
Control
Raw material
Material
Structure
Speed
Condition
Function
Productivity
Purpose

Phenomena（Flow and Diffusion）

- Pulling up a single crystal
  - ✓Using seed crystals
  - ✓Avoid nucleation
  - ✓Precise temperature control
  - ✓Quiet flow

Flow：laminar and turbulent flow

- **Laminar flow（not mixed）**
  - ✓ Able to follow streamlines
- **Turbulent flow（well mixed）**
  - ✓ Flow with vortices
  - ✓ Unable to follow streamlines

the movie here has been removed due to a copyright issue.

Reynolds number

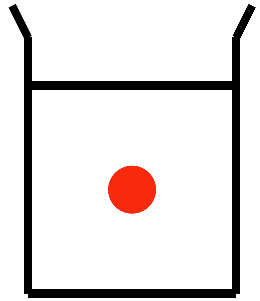
$$\mathrm{Re} = \frac{dv\rho}{\mu}$$

d : typical length
v : velocity of fluid
ρ : density of fluid
μ : viscosity

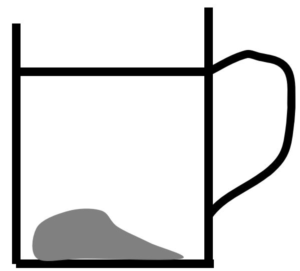
Realizing a "diffusion"

liquid diffusion and solid diffusion

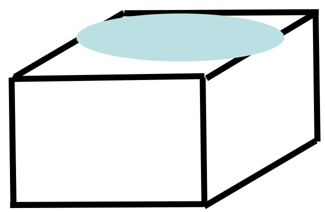
A stain when you put some ink into water



Put a lump of sugar into water,
and wait without shaking



Coat a block ice with sugar
Ice with strawberry syrup



‡

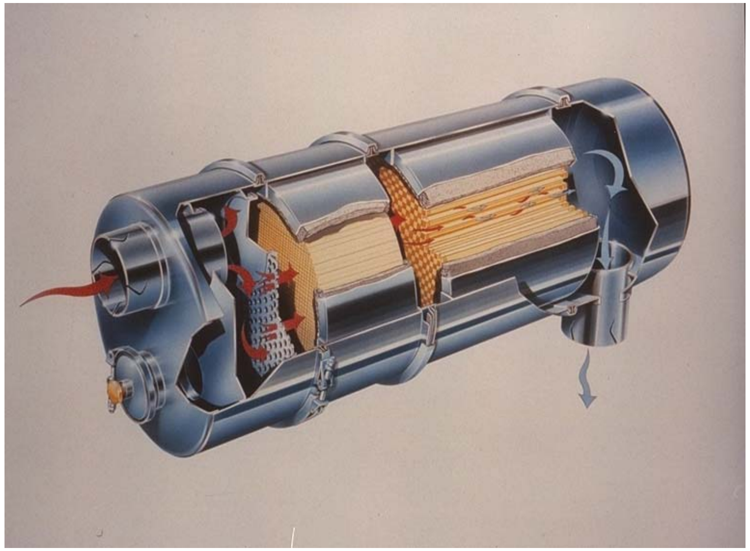
Vapor-phase diffusion

Collides 5 billion times per second when running 0.1 μm at the speed of 500 m/s

Automobile emission gas purifying catalyst

Honeycomb type

Honeycomb catalyzer



Unique Patented Johnson Matthey System

Passing through a tube whose diameter is 5mm at 500m/s

All of the molecules make contact with the catalyst on the wall

Let us return to the main subject…

Molecules on a cup of pure water

One molecule of impurity (electron) in a nanodot

II-2. Soft matter

LCD displays, Color Films,
Color Filters, Molecule sensors

Substance（molecular structure・molecular design）・**Structure**（form）
Speed（multi-layer coating・ink jet）・**Conditions**
Phenomena：
Self-Organizing, Chemical reaction, Flow (driven by surface tension)

LCD Displays

Molded plastic products

Robots
（sensors made of conductive high molecular material）

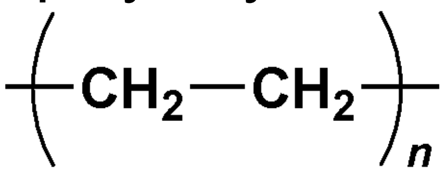
Amphipathic organic molecules

Micelle（soap・cosmetics）

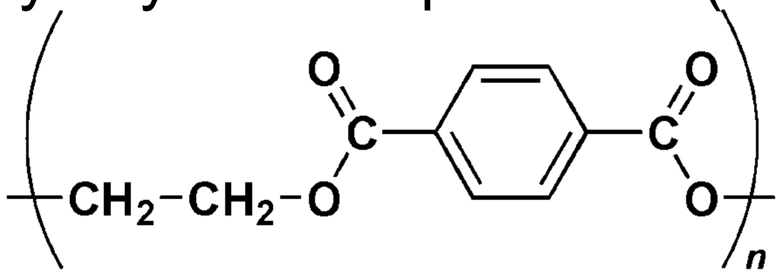
1. Characteristics of Soft matter

	Organic material	Inorganic material	metal
	Soft matter	"Hard" matter	
Building block	molecule	atom	
When they show their characteristics	one molecule molecular ensemble	Atomic ensemble	
Bonding force	Intermolecular force (comparatively weak)	Covalent bonding (comparatively strong)	Metallic bonding

polyethylene



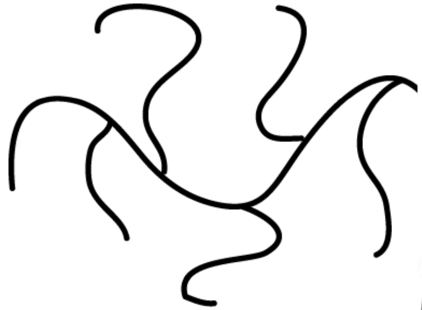
Polyethylene terephthalate (PET)



2.1 branched polymer and straight-chain polymer

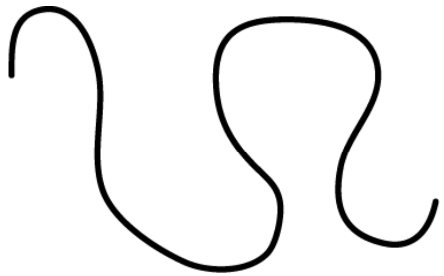
Branched polyethylene

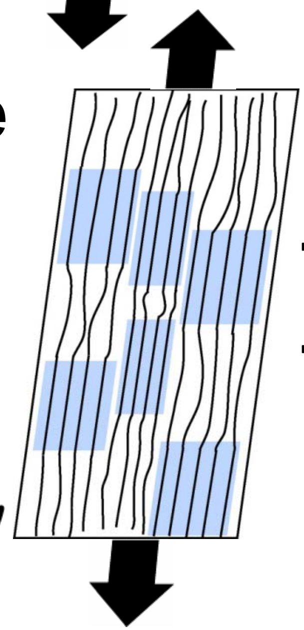
- High pressure, oxygen radical polymerizatio
  → irregular structure
  (branched structure)



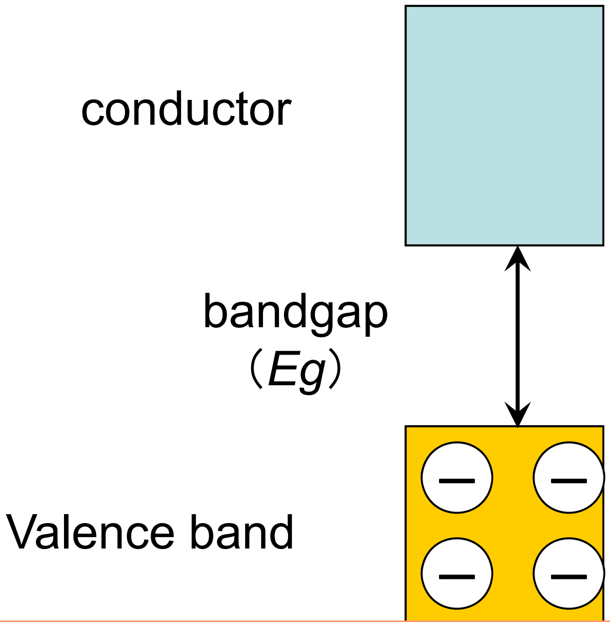
Straight chain polyethylene

- Low pressure, catalyst polymerization
  → regular structure
  (normal chain structure)

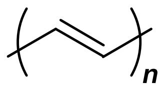
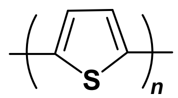
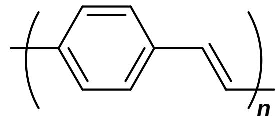




2.2 polymer semiconductor



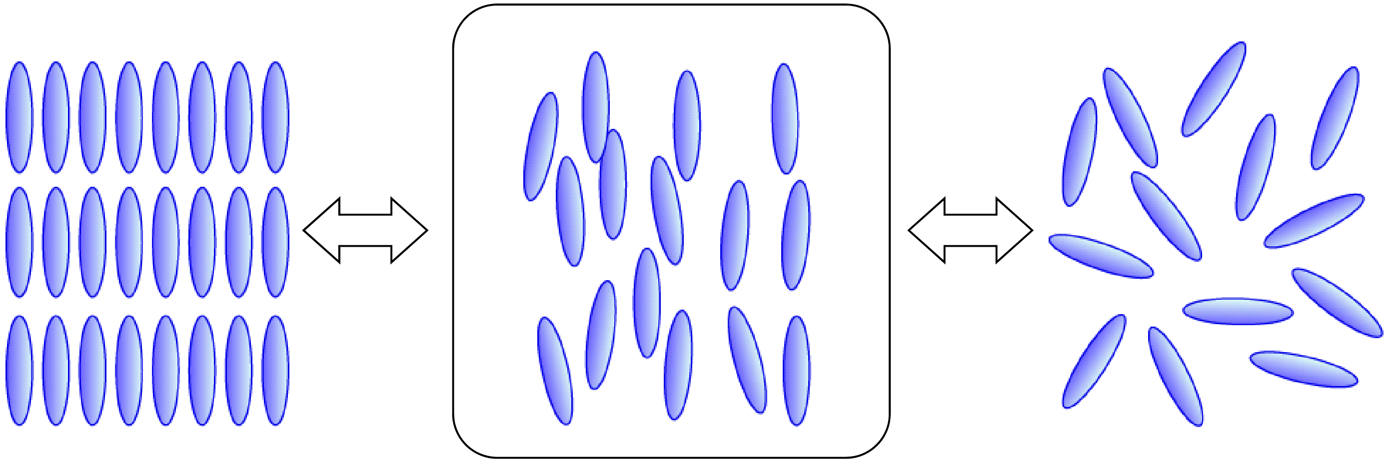
What are possible with polymer semiconductors

	compound	*Eg* (eV)
Conductive polymer	polyacetylene 	1.4
	polythiophene 	2.0
	PPV 	2.5
Inorganic	Si	1.12
	GaAs	1.42

- flexible as paper, write/delete figures on devices ➡ Electronic paper
- molecular level(nm scale) ➡ Sensors such as Superfine complex elements, and living molecules
- Structure similar to living molecules ➡ Self-restoration

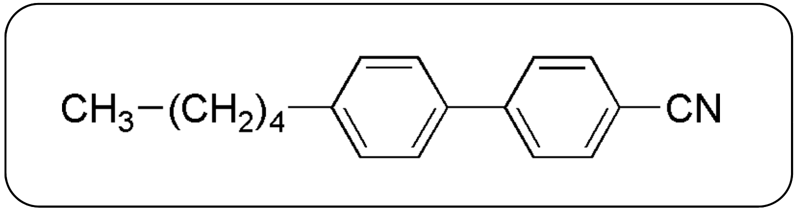
- Semiconductor soft matter is easy to mold and transform
- It is possible to adjust Eg using chemical modification
- The electric conductivity of doped semiconductor is as high as metals

2.3 liquid crystals (functional soft matter)



crystal | Liquid crystal | liquid

temperature —— 22.5℃ —— 35℃ ——→



‡Provided by Prof. Kato, The University of Tokyo

3 manufacturing process : example 1

Making up μm size structure

Multilayer structure of photo film
(multilayer coating, multilayer film formation)

- controlling laminar flow
- **controlling longitudinal diffusion**
- **controlling drying process**

the movie here has been removed
due to a copyright issue.

Is Diffusion good or bad for technologies?

	Good (application of diffusion)	Bad (how to cope with diffusion)
Gas phase	**Film forming equipment** **Honeycomb catalyst**	**optic fiber (particulations in rapid reaction)**
	Purification (gas phase or liquid phase)	
Liquid phase	**liquid phase reaction (stirring: diffusion of particles of molecular size)**	**Multilayer film forming (high-speed pull up)**
Solid phase	**doping** **optical fiber (smooth distribution)**	**Akashi fiber (alloying)**

3 manufacturing process : example 2

Making a surface with μm size structure

Making Color filter using ink jet mechanism (Bottom-up process)

the movie here has been removed due to a copyright issue.

4. Nanometer scale manufacturing

4. 1 self-assembled phenomenon

Spontaneous structure formation of molecules and atoms (clusters) with their form constant

What to expect
- formation of fine structure
- Energy saving
- low environmental burden

Thermo-dynamics	equilibrium	Dissipative system
examples	**Crystal** **Liquid Crystal** **Self-assembled monolayers** **Phase separation**	**Turing model** Belousov-Zhabotinsky reaction **Liesegang Phenomenon** **Wind patterns on sand** **Band on a tropical fish** **Forest**

Self-assembly : examples

non-equilibrium systems in terms of thermodynamics
(oscillations in sandhills, forests, and chemical reactions)

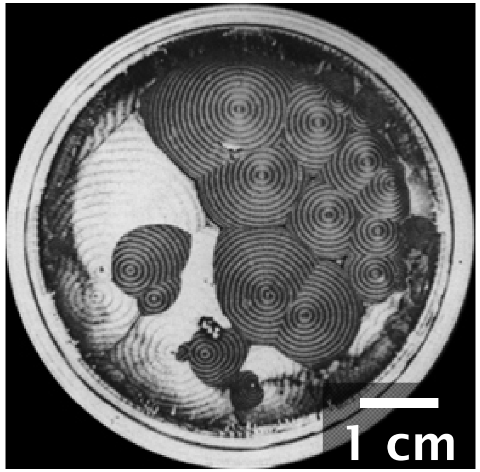
Wind patterns on the Tottori Sand Dunes

‡Tottori Pref., Dept. of Culture and sightseeing,
Kanko-Seisaku section

Forest（Mt. Tateshina, Shimagare phenomenon）

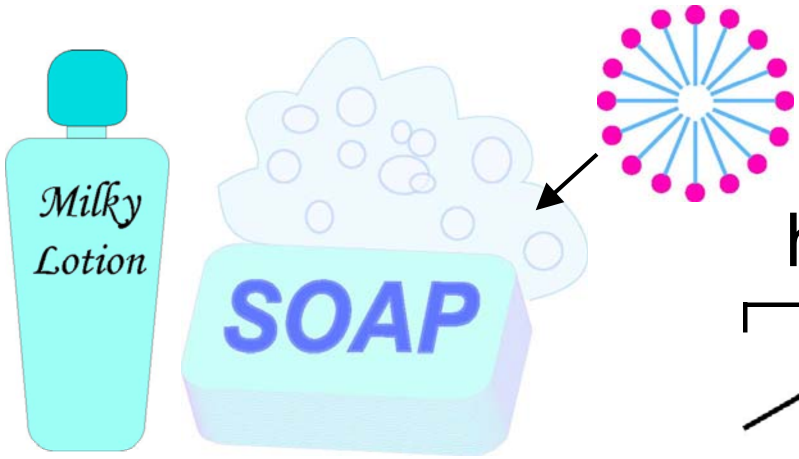
‡Nagano Pref., Hara Village, Sightseeing association

Ascorbic acid crystal develops along with the evaporation of the medium (Liesegang Phenomenon)

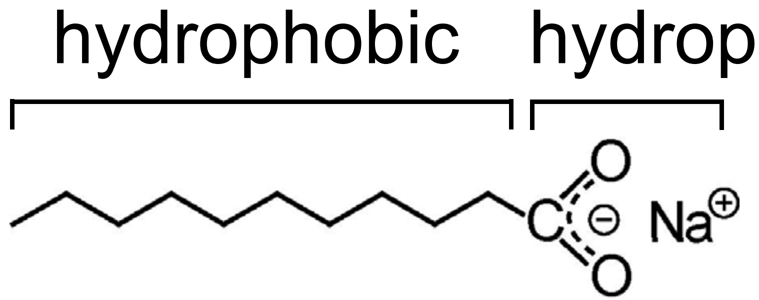


‡K. Iwamoto et al.,
J. Colloid Interface Sci.
102, 477 (1984).

4．2 self-assembly of amphipathic molecule



Micelle (soap)

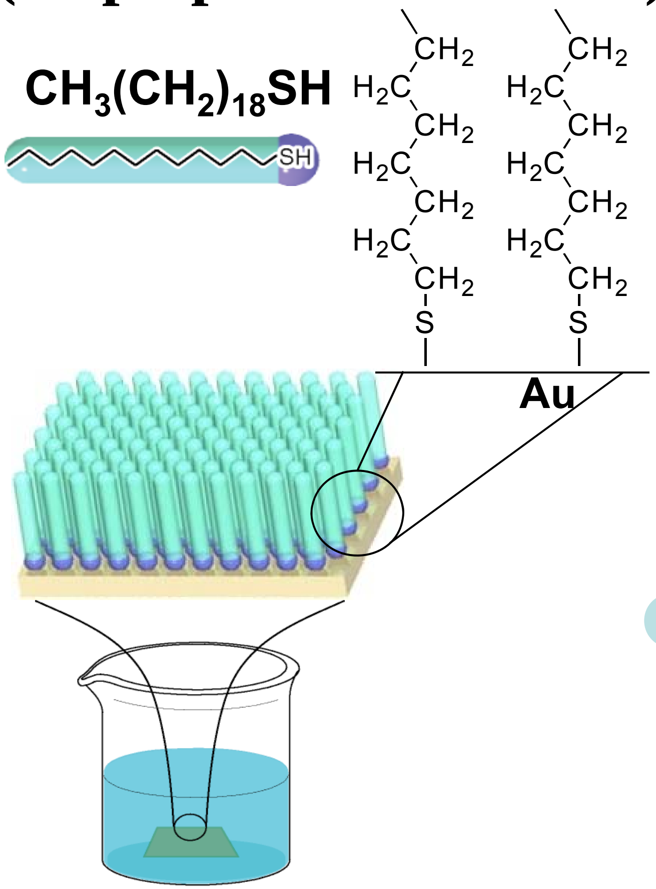


self-assembly on a substrate

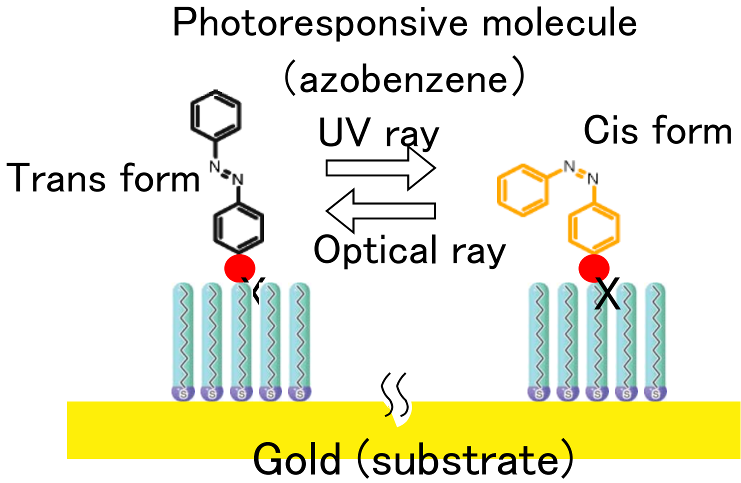
Functionalization at molecular level
(self-assembled monolayers)

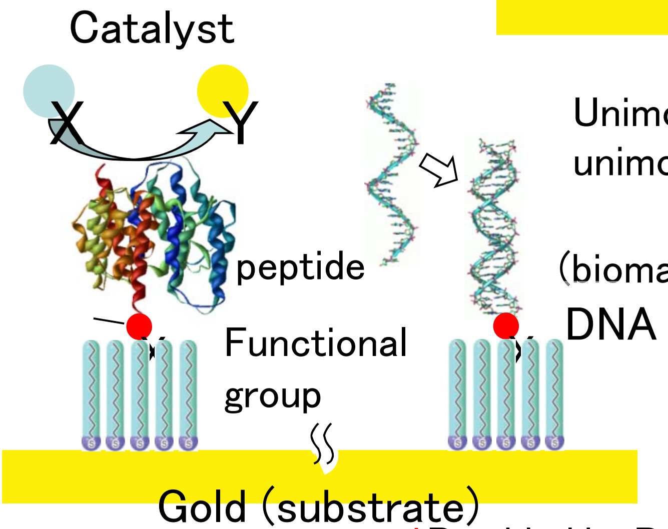
Self-assembled monolayers (two-dimensional crystalization on a substrate)

(amphipathic molecules)



Optical memory/sensor





‡Provided by Prof. Kato, The University of Tokyo

Surface tension is dominant in microscopic systems

- Surface tension / gravitation

$$\frac{\sigma \times circumference}{g\,\rho \times volume} = \frac{\sigma}{g\,\rho\, r^2}$$

the ratio is ~10^7
In micrometer-size water droplet

σ : surface tension[N m^{-1}]

g : gravitational accerelation[m s^{-2}]

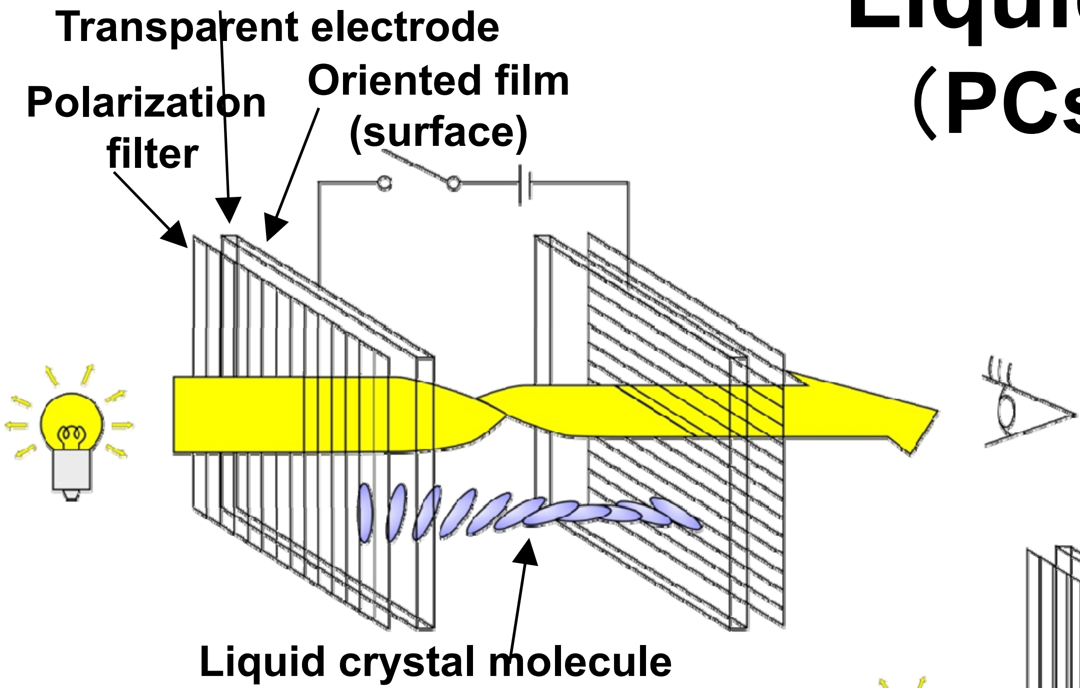
ρ : density [kg m^{-3}]

r : radius of droplet [m]

4.4 Self-assemblying soft matter:Liquid Crystals

4th phase of matter : Solid, LC, Liquid, Gas

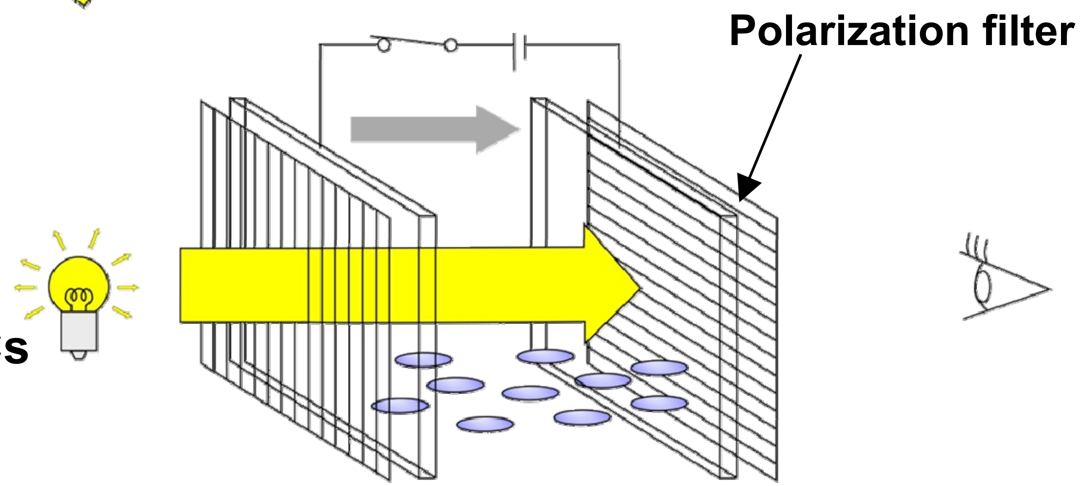
＜Electric field ON＞



Liquid Crystal Display （PCs, Mobile phones）

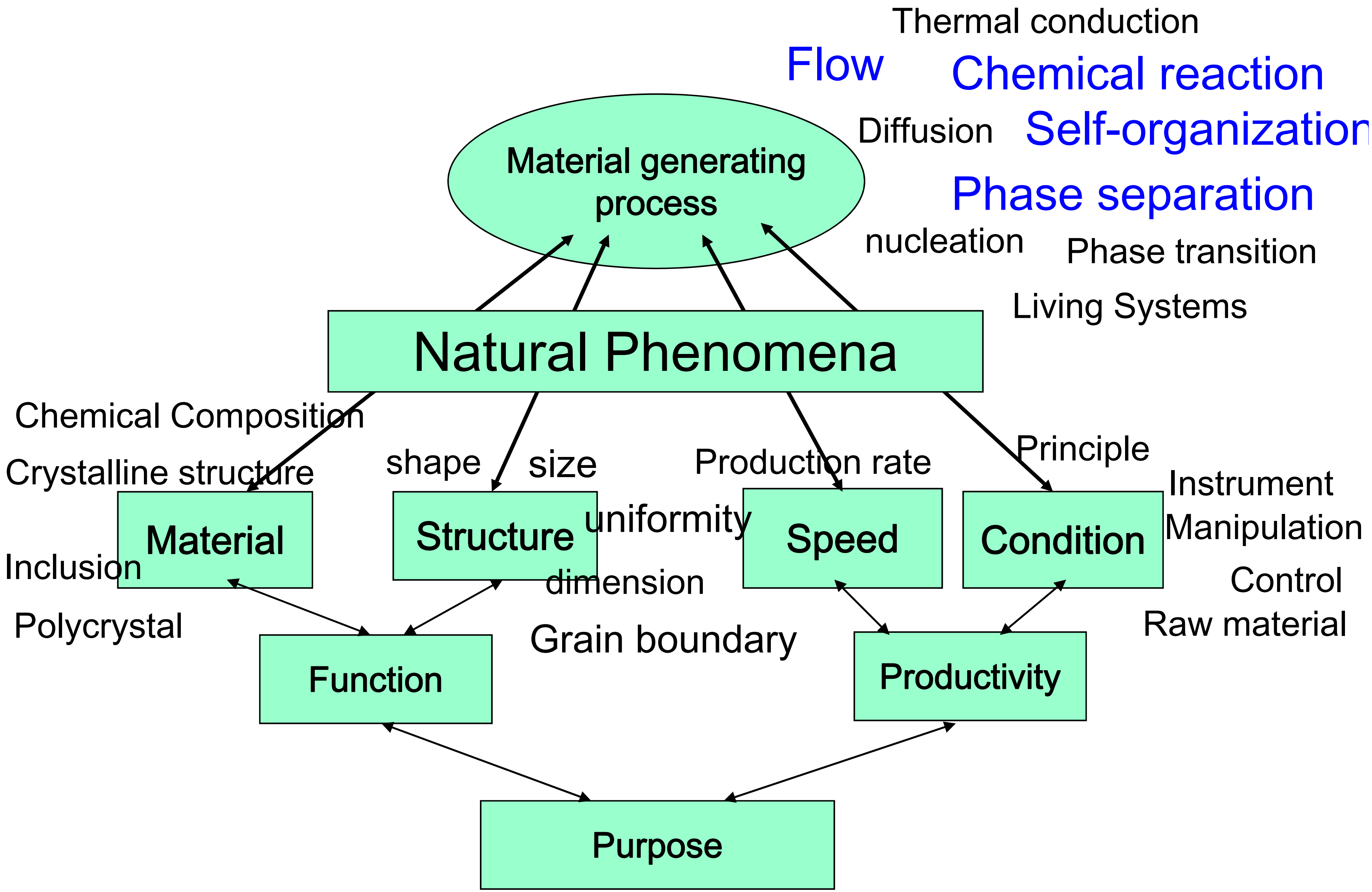
＜Electric field OFF＞

a pair of polarization filters keeps the light from passing through
(LCD is in “Dark” state)



Electric field twists the array of LCs by 90 degrees to rotate the optical polarization surface, making LCD visible (“Bright” state)

‡Provided by Prof. Kato, The University of Tokyo



Thermal conduction
Flow
Chemical reaction
Diffusion
Self-organization
Material generating process
Phase separation
nucleation
Phase transition
Living Systems
Natural Phenomena
Chemical Composition
Crystalline structure
shape
size
Production rate
Principle
Instrument
Manipulation
Material
Structure
uniformity
Speed
Condition
Inclusion
dimension
Control
Polycrystal
Grain boundary
Raw material
Function
Productivity
Purpose

Q&A cost calculations

When 1 automobile costs ¥100 billion,
100 million cost ¥100 million

Cost = (raw material) ＋ (equipment)＋ (personnel)

Reducible cost and non-reducible cost

Relocation costs：¥200 billion → ¥50 billion

Misunderstandings about the recycle costs

Brush up your ability to predict future prices!

Semiconductor devices

Phenomena
- flow : laminar and turbulent flow
- diffusion: Gas, Liquid, Solid
- heat transfer: conduction
- (Thermal conductance × temperature gradient)
- comparison: diffusion
- (diffusion coefficient × concentration gradient)
- radiation, convection
- chemical reaction, self-organization

Soft matter

Matter and structure ⇨ function

Matter (molecule and ensemble design)

structure, speed, condition

phenomena
- laminar flow control, diffusion control
- self-orgnization
- surface tension, marangoni convection
- phase transition

Next lecture: Materials science for a sustainable future