Global Focus on Knowledge

Production and Application of Matter

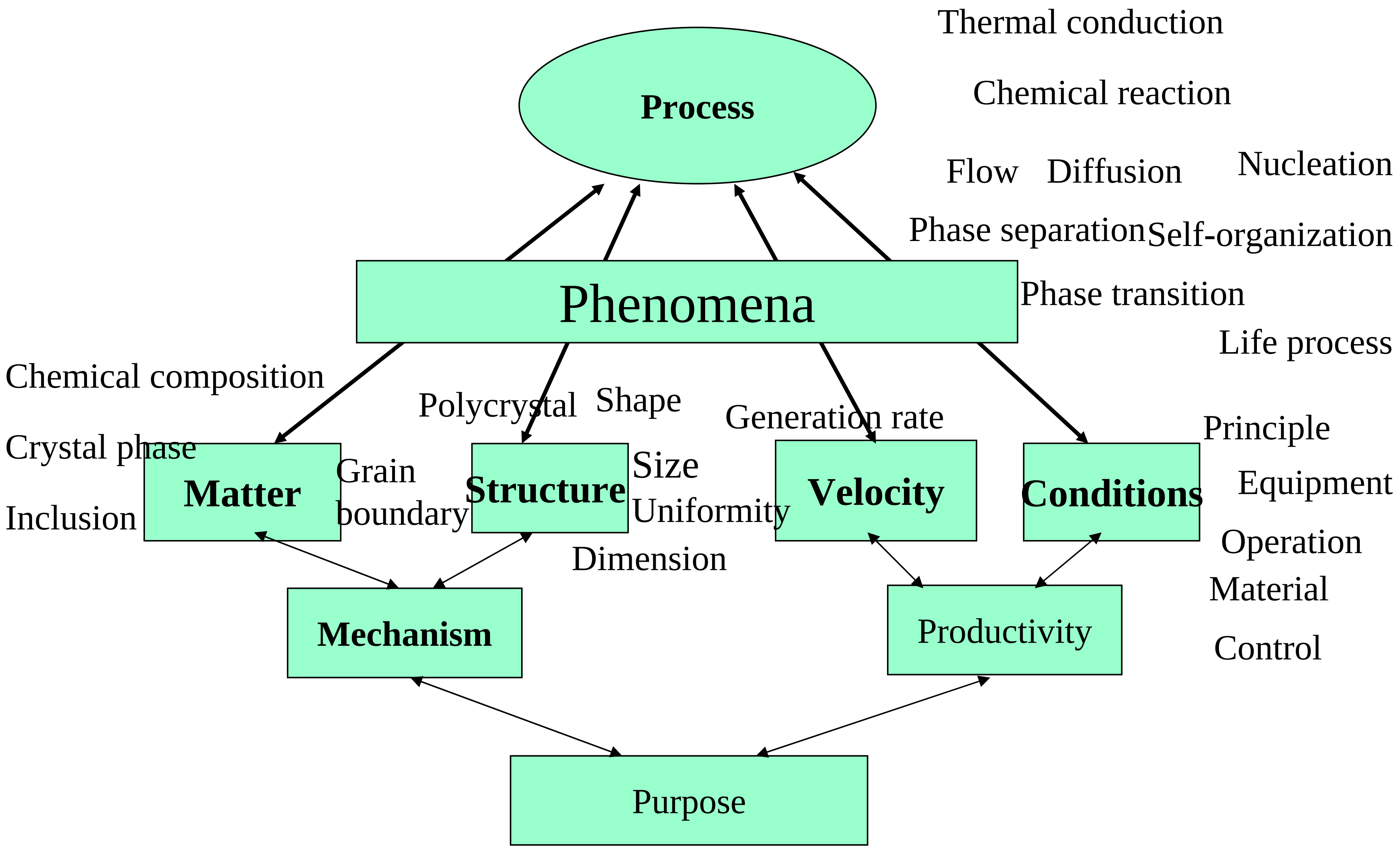
The University of Tokyo Hiroshi Komiyama

Lecture One: The production process of matter, e.g., metals (iron and steel).

Lecture Two: Conjugation (device), e.g., semiconductors and inorganic materials.

Lecture Three: Soft matter, e.g., liquid crystals.

Lecture Four: Matter in durable earth (device), e.g., fuel cells and biochips.



Thermal conduction
Chemical reaction
Process
Flow
Diffusion
Nucleation
Phase separation
Self-organization
Phenomena
Phase transition
Life process
Chemical composition
Polycrystal
Shape
Generation rate
Principle
Crystal phase
Matter
Grain boundary
Structure
Size
Uniformity
Velocity
Conditions
Equipment
Inclusion
Operation
Dimension
Material
Mechanism
Productivity
Control
Purpose

Introduction

Semiconductor devices,
optical fibers, catalytic reaction apparatus,

composition, structure (shape and size in particular),
and velocity.

Phenomenon: flow, diffusion and thermal transfer.
(In a previous lecture: nucleation and phase separation)

Characteristics of Semiconductors

Impurity insertion, optical irradiation, and electrical fields become the causes of enormous changes in electrical conductivity.

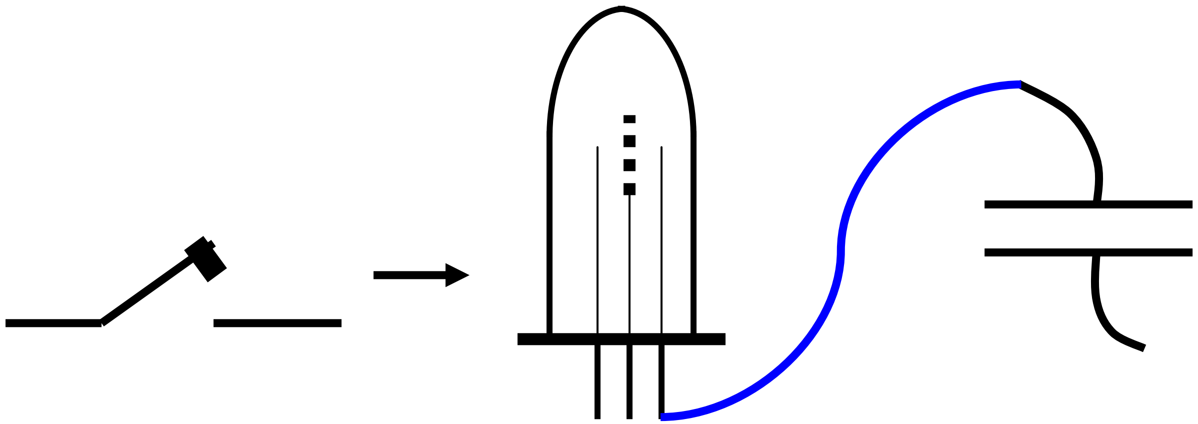
(Transformation of physical properties to 10 digits.)

Metal：$10^{-6} \sim 10^{-4}\ \Omega$-cm

Semiconductor：$10^{-3} \sim 10^{8}\ \Omega$-cm

Insulator：$10^{10}\ \Omega$-cm<

Memory Cells are Made of a Control gate and a binary cell



Mechanical switch

Vacuum tube Electric condenser

$Q = CV$

A Brief History of Semiconductors

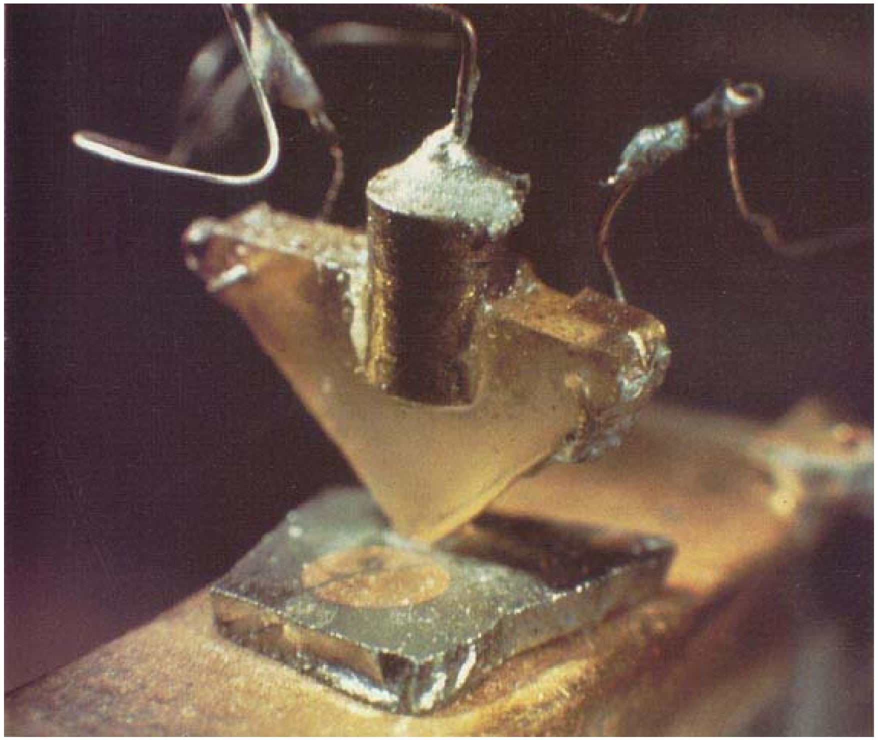
- Coexistence of vacuum tubes and solid-state devices.
- Invention of the transistor. (1947)
- Germanium (1950’s)
- Silicon and Integrated Circuits (IC). (1960’s)
- Ultra Large Scale Integration (ULSI). (1970’s-)
- Giga-scale Integration (GSI). (21C)
- ???Quantum devices???

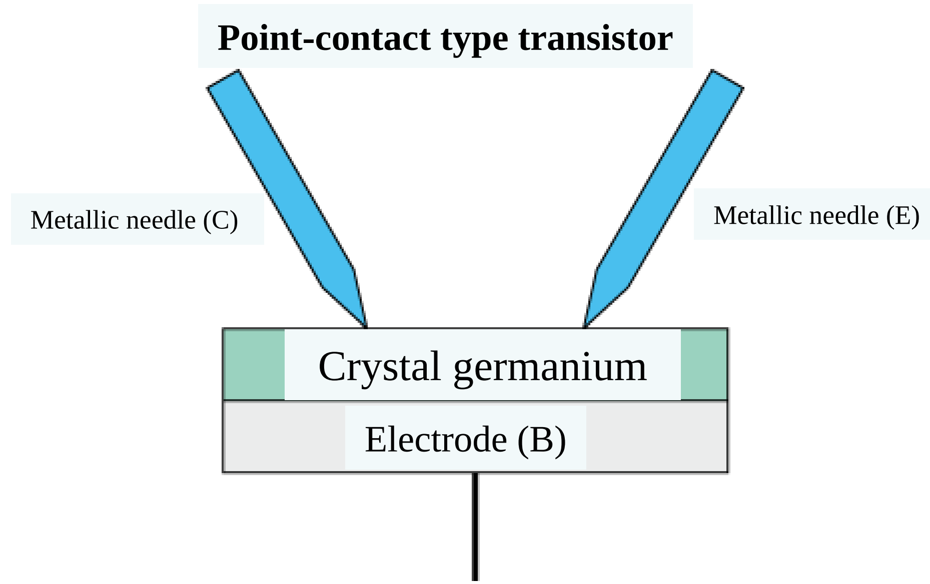
Characteristics of Semiconductors

	Si	Ge	GaAs
Eg (eV)	1.12	0.68	1.42
Transitive	Indirect transition	Indirect transition	Direct transition
Electron mobility (cm^2/Vs)	1450	3900	9200
Hole mobility (cm^2/Vs)	500	1900	320

- Highly-reliable oxide film on Si.
- The oxide film on Ge is unstable. (Even soluble in water.)
- III-V family compound semiconductors (e.g., GaAs) are difficult to work with.
- III-V family compound semiconductors (e.g., GaAs) are highly luminous.

The Invention of the Transistor by Bell Labs in 1947

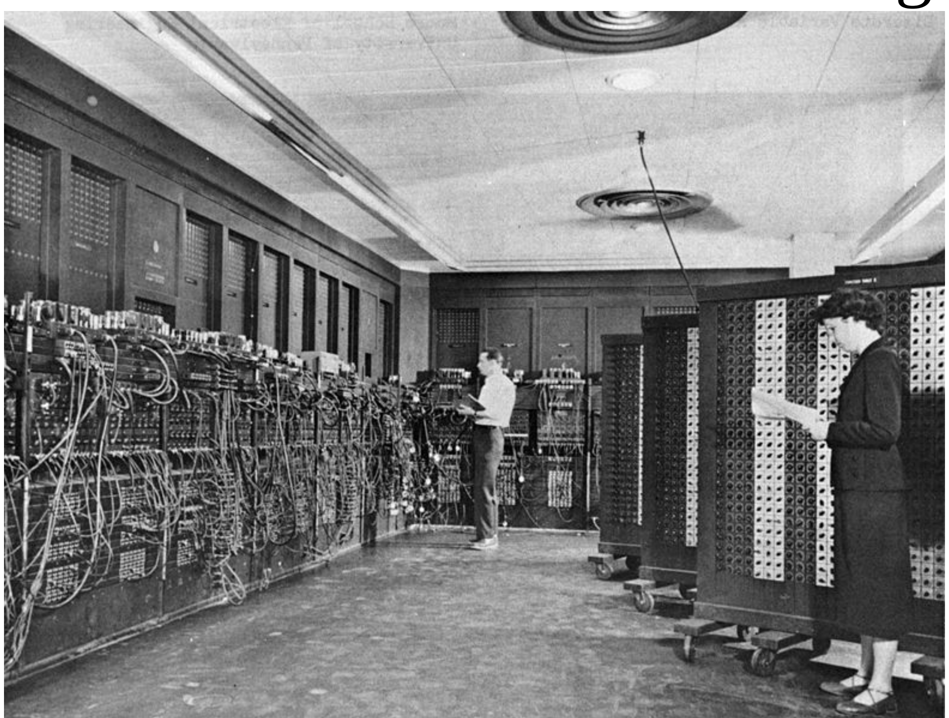




December 16, 1947.
Transistor action was observed.

The Vacuum Tube was Replaced by the Transistor

Transistors featured low power consumption, were highly reliable, and had long life.

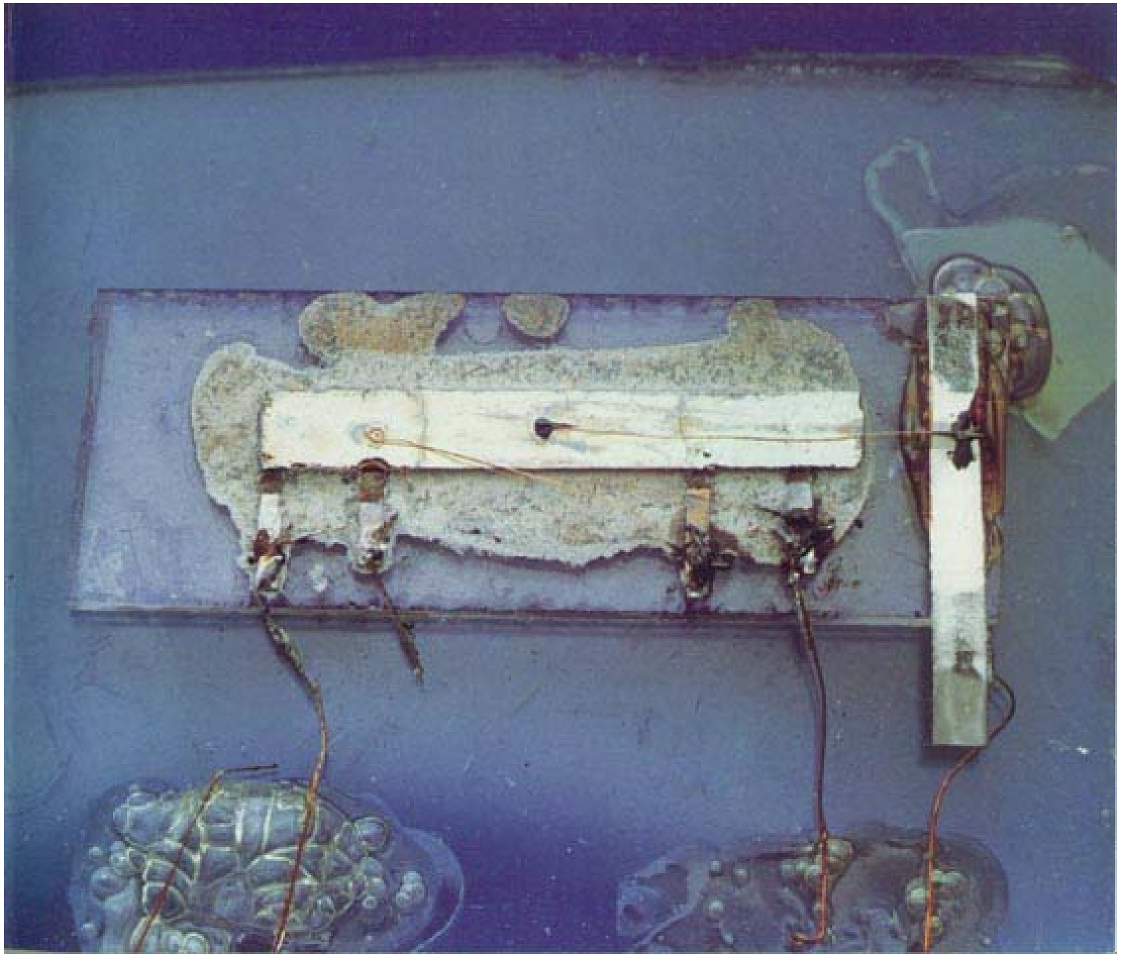


Wikipedia

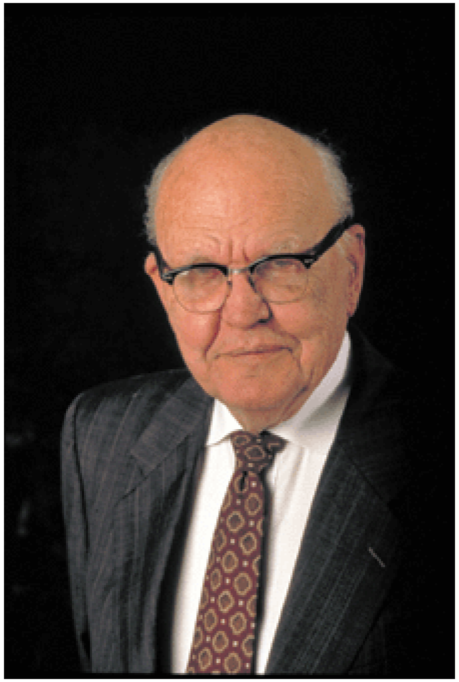
ENIAC（Electronic Numerical Integrator and Computer）was the world's first electric digital computer equipped with 18,000 vacuum tubes. It took three seconds to compute a ten-digit ballistic trajectory.

- ●Power consumption：140kW.
- ●Life span: several hours.

The First IC in 1958



Photos courtesy of Texas Instruments



Texas Instruments Inc.
Dr. Jack Killby's invention
in 2000.
He was awarded the Nobel
Prize for Physics.

From Transistors to ICs

- Development of the transistor.
  - Radar (military purposes).
  - Telephone exchange operation by AT&T (←mechanical cable type).
  - Use in the transistor radio by Sony.
  - Large computers by IBM.
- The transistor was gradually replaced by the IC.

The Source of High Accumulation

① Speed-up the transistor by dividing it; the working speed is raised to k～k^2 times when the the transistor is divided as small as 1/k.

② Multifunctionalize the transistor by accumulating multiple functions.

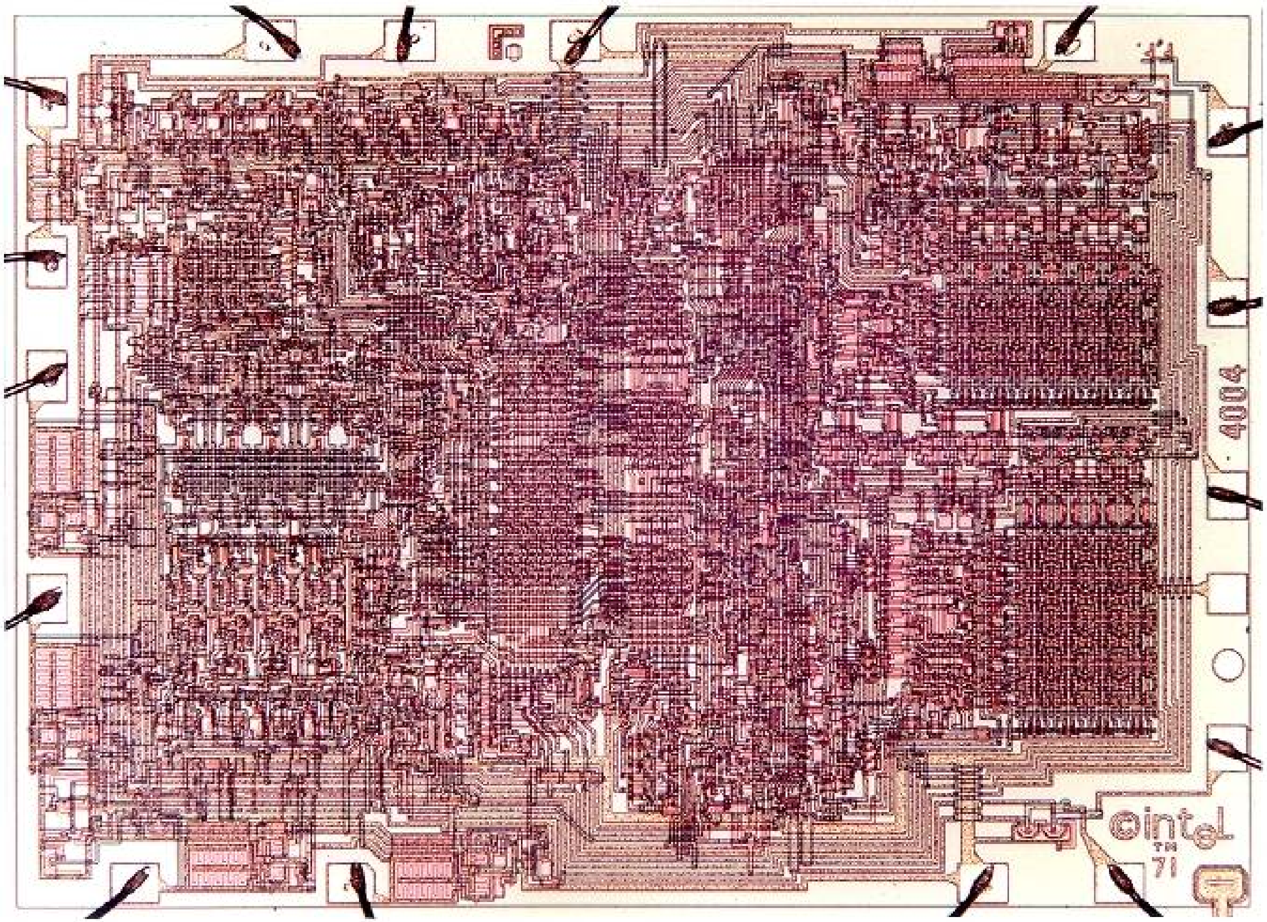
Mixed loading of CPU, graphic circuit, and memory.

→Achievement of a single-chip computer

① Economical efficiency.

E.g., A lower price-per-bit.

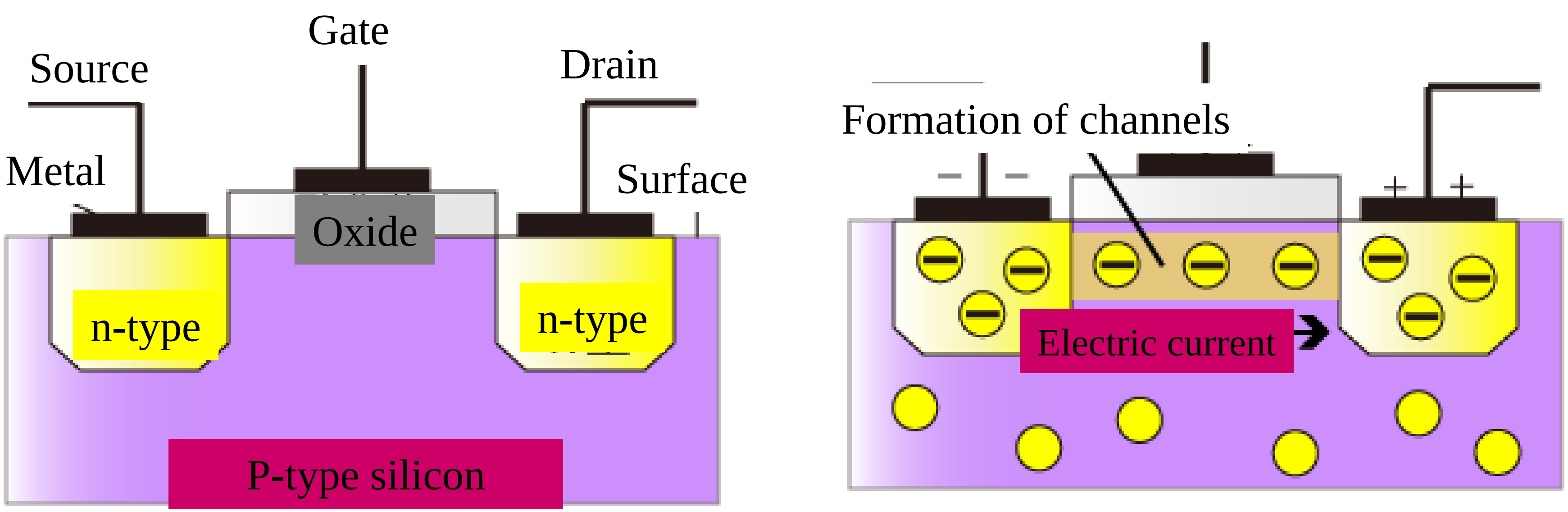
The First CPU Built by Intel in1971



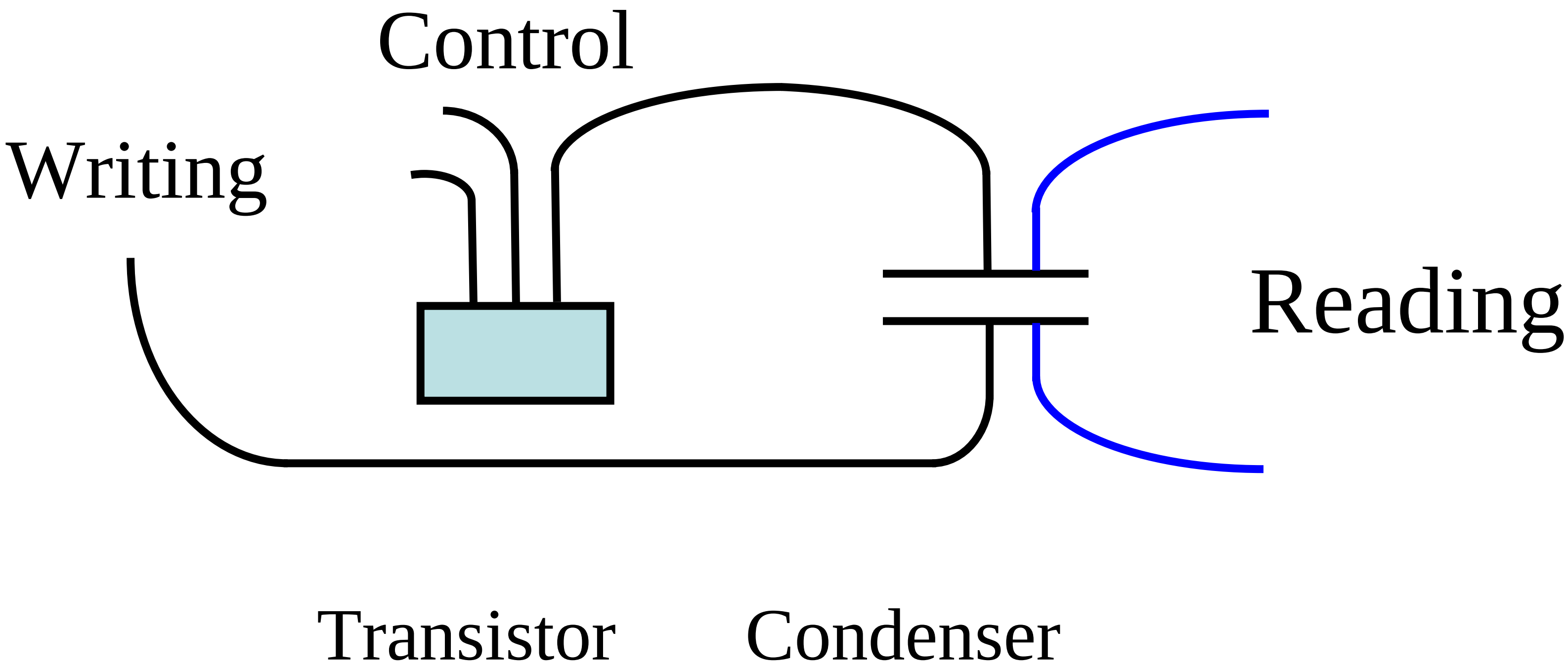
Busicom Corp. chose Intel to develop an electric calculator-based-CPU. Shima Masatoshi was one of the team members who completed the work.

MOS Transistor

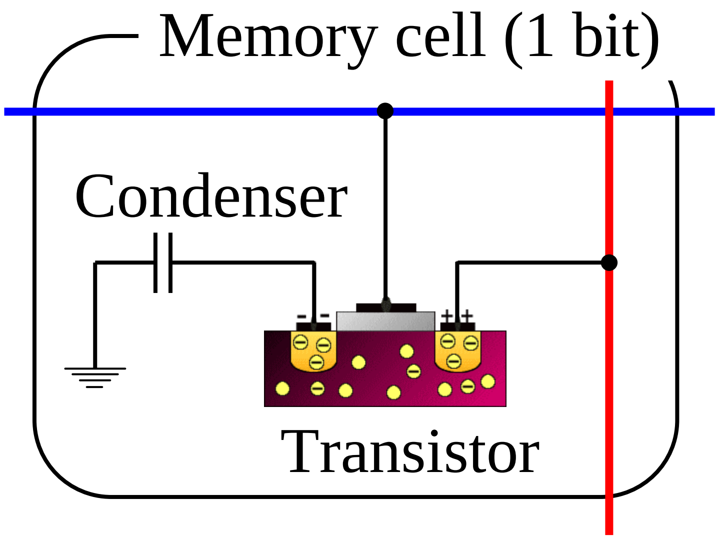
- **<u>M</u>**etal-**<u>O</u>**xide-<u>S</u>emiconductor Structure.
- Turns on/off the electric current that runs from the source to the drain via the electric voltage applied on the gate.

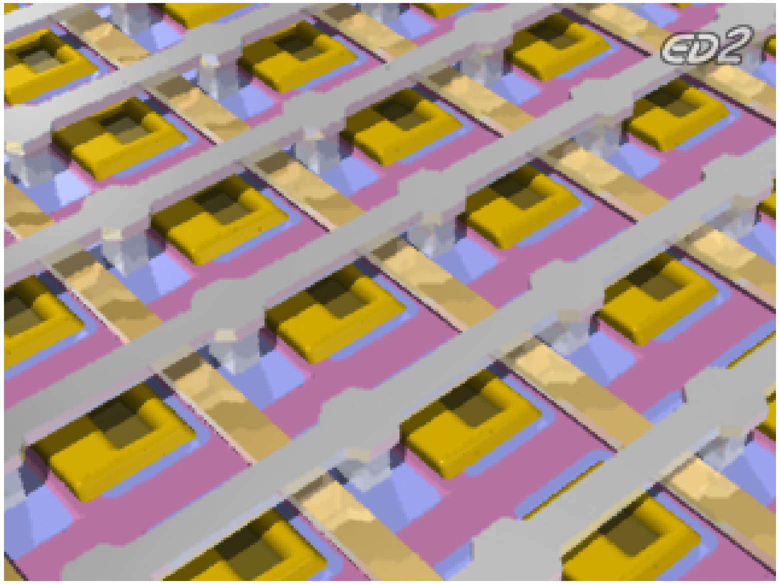


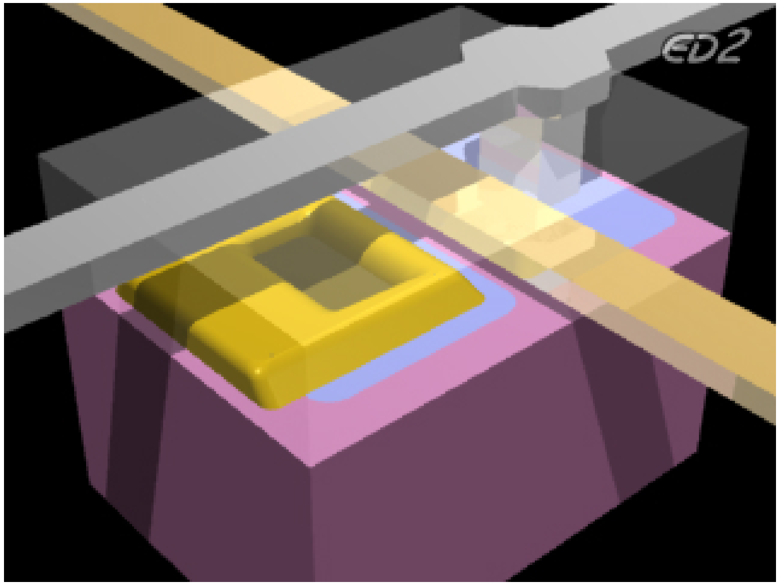
A Memory Cell is Made Up of a Control Gate and a Binary Cell

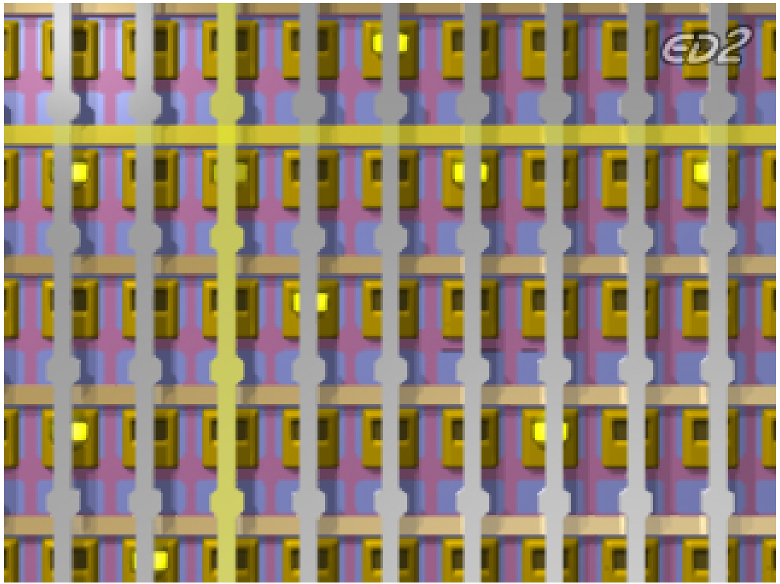


Structure of a DRAM

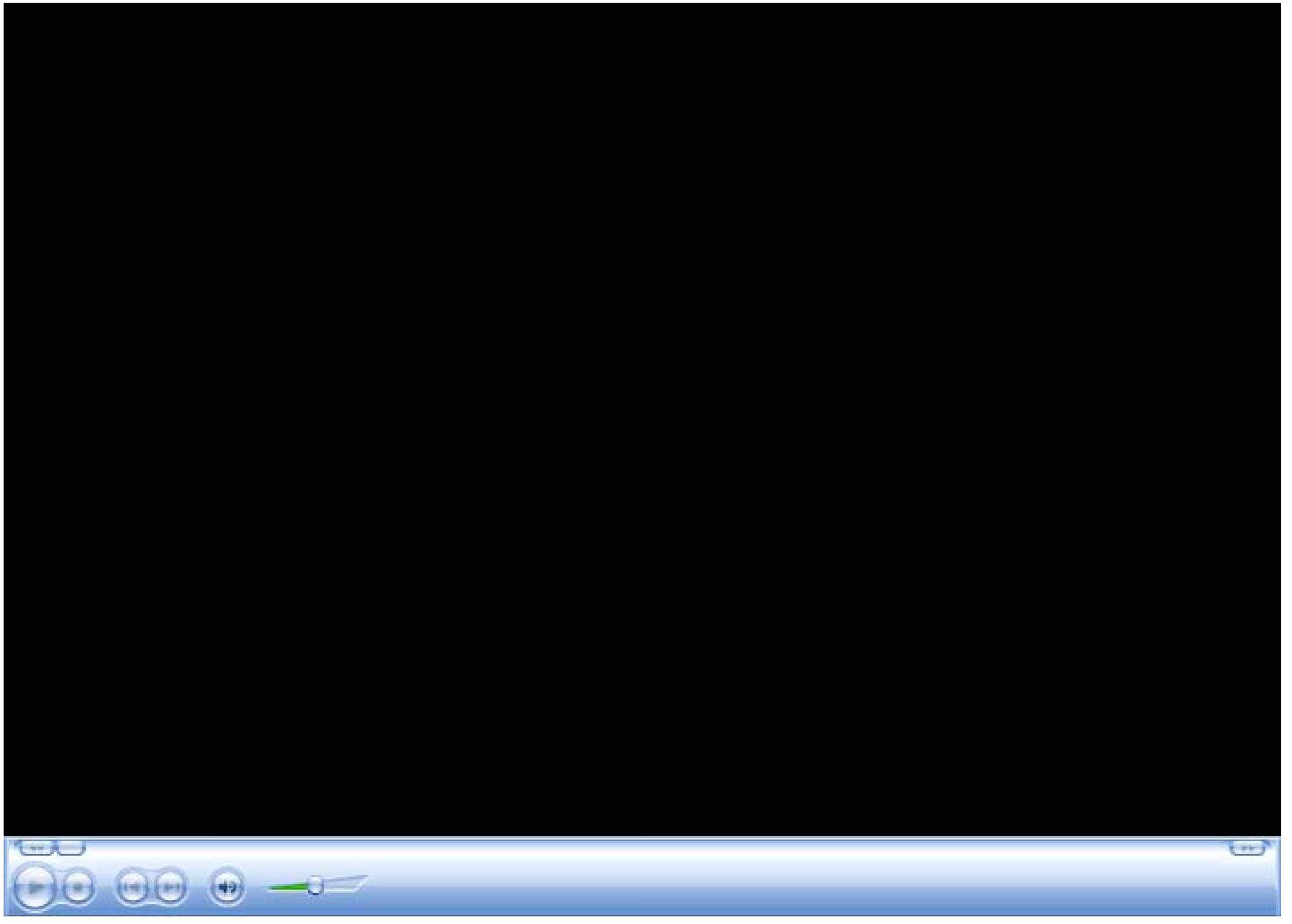








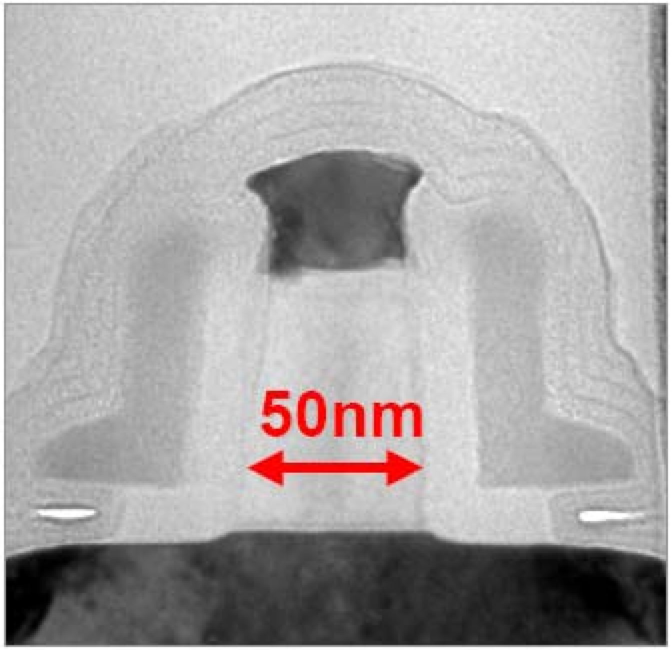
Structure of a DRAM and its Operating Mechanism (Animation)



Transistor 1/k

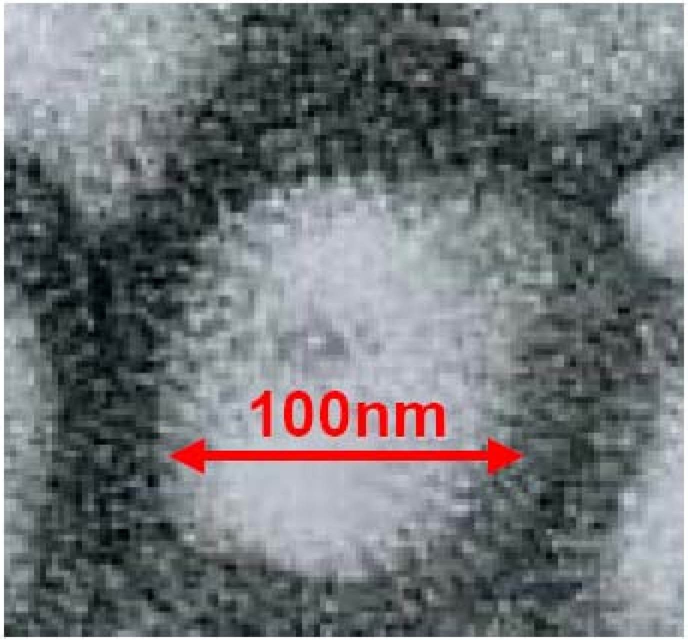
	Constant electric field	Constant voltage
Supply voltage	1/k	**1**
Electric field	**1**	k
Working speed	k	k^2
Energy consumption	$1/k^2$	k
Major purposes	Low energy consumption mobile device	High speed processing CPU

Some Transistors Are Already Smaller Than a Virus!



Transistor for 90nm process

‡ Source: Intel



Influenza virus

Source: CDC

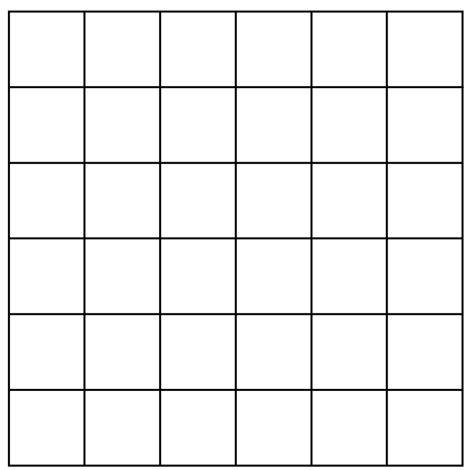
Necessity for Nanotechnology

1 giga memory 10^9

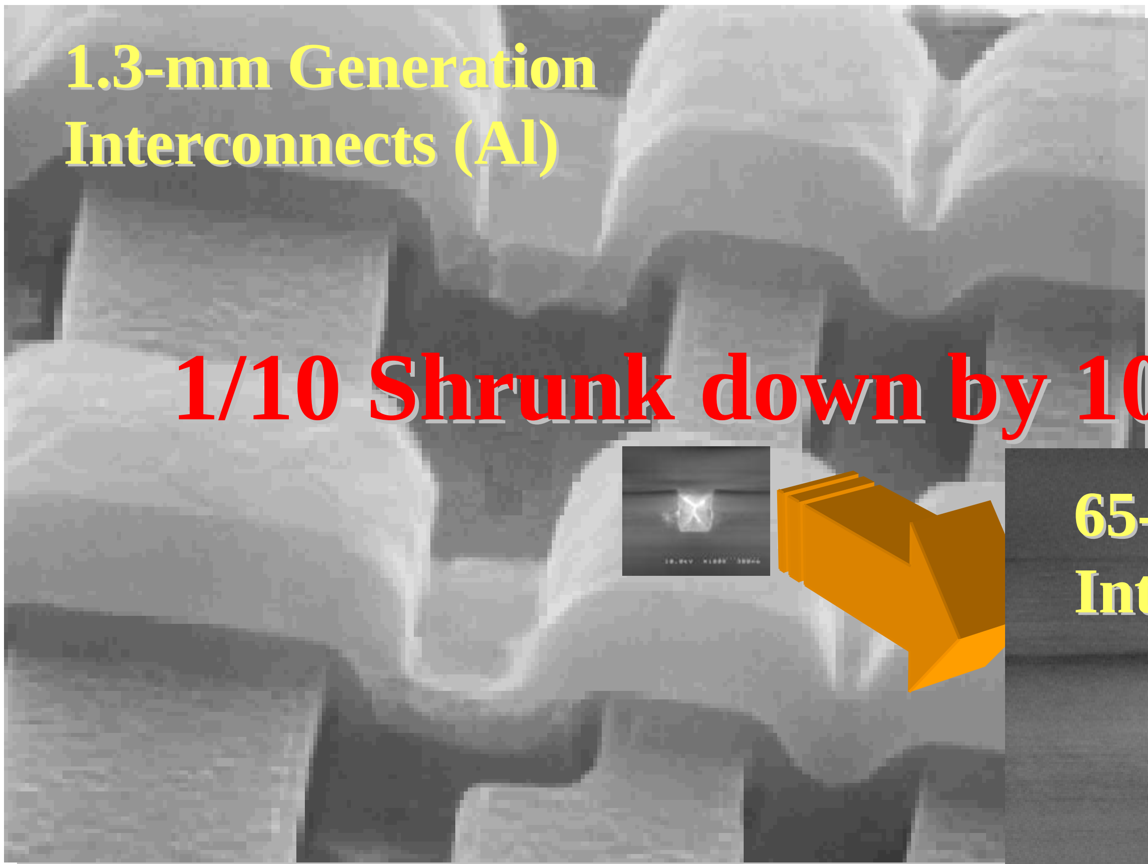
$= (3\times10^4)\times(3\times10^4)$

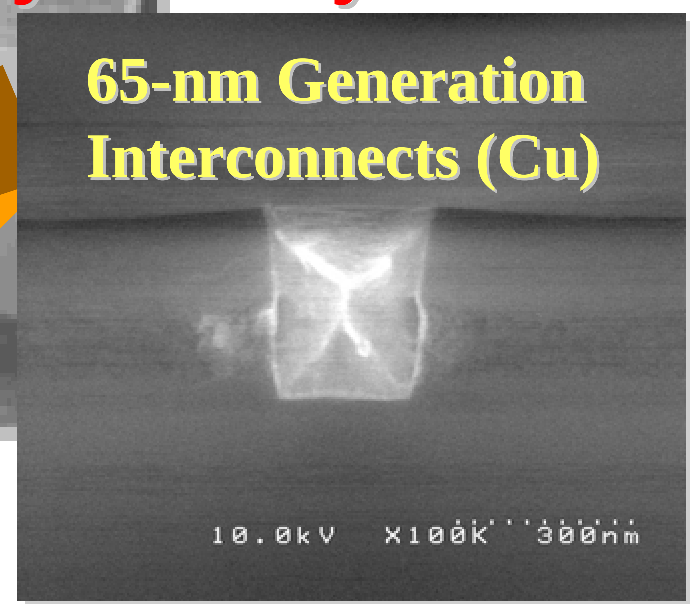
1 cm × 1cm (chip)

= 0.3 micron × 0.3 micron (device)



Wiring is Difficult (Multi-layering and Minute Division)





source: Prof. Takayuki Ohba, Institute of Engineering Innovation, School of Engineering, University of Tokyo

Making High-purity Silicon

① Reduction of SiO_2 at 1,200℃.

SiO_2 + C → Si（purity 98%） + CO_2↑

② Trichlorosilane production.

（Liquid chemical is used.)

Si + 3HCl → $SiHCl_3$ + H_2↑

‡ 

Source: Sumco Corporation
http://www.sumcosi.com/laboratory/laboratory1.html

① Purification process by distillation.

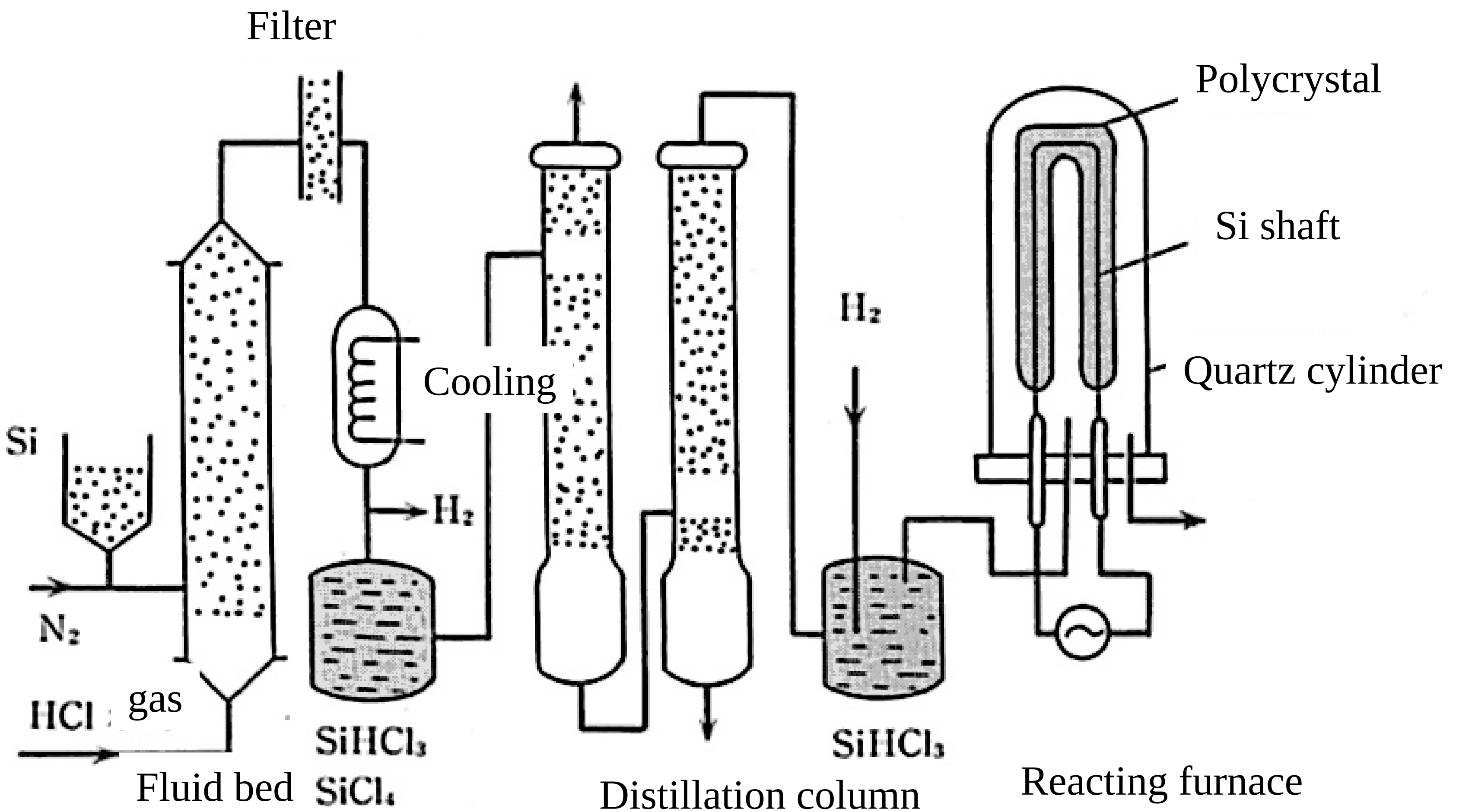
$SiHCl_3$（98%） → $SiHCl_3$（99.999999999%）

② Composition of solid state high-purity Si through CVD process.

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

Silicon Purification Process

Impurity-rich silicon decomposed to the high-purity silicon.



Katsuro Sugawara, Hiroshi Fukuda (1995) “Super LSI Processing”

Baifukan, P55 Chart4.27

High-purity Polycrystal Silicon Production (Animation)

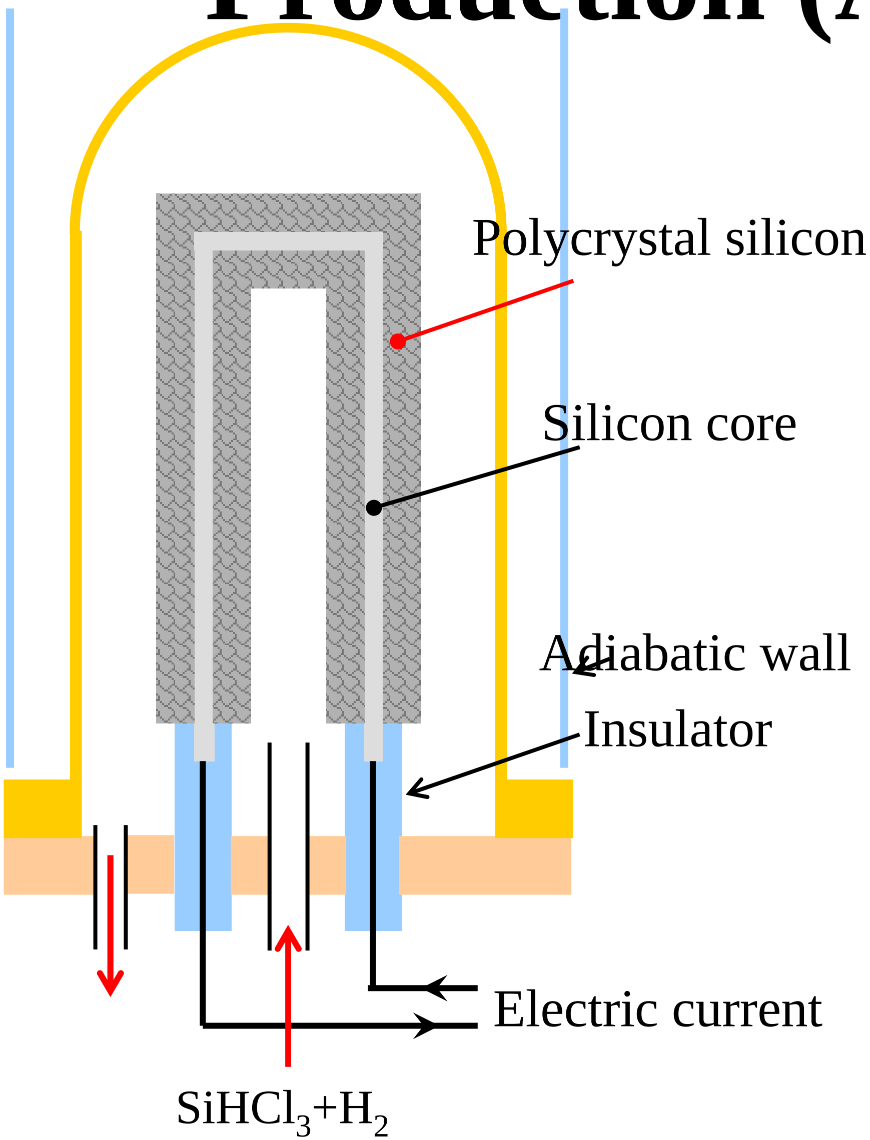
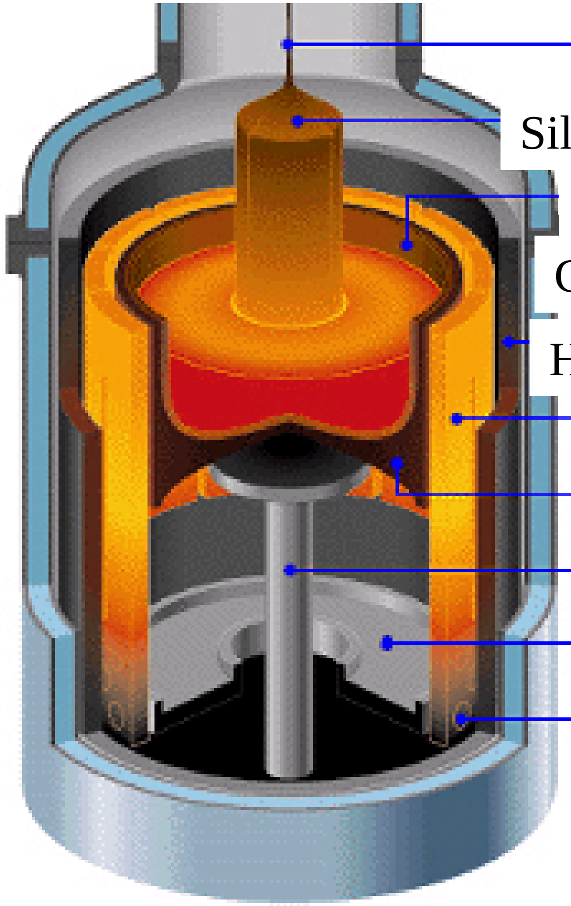


Figure removed due to copyright restrictions

Monocrystal Si Ingot Pulling

<u>CZ furnace: structure drawing</u>



Czochralski (CZ) method

① Dissolution of high-purity polycrystal silicon at high temperature in the crucible.

② Pull the crystal while a tiny seed crystal is welded together with molten silicon to obtain precipitation.

Sumco Corporation
http://www.sumcosi.com/laboratory/laboratory1.html

Production of Monocrystal Silicon Wafers (Animation)

Figure removed due to copyright restrictions

Komatsu Electric Metals Co., Ltd.

The Basics of Fine Processing

Pattern formation (lithography).

① Resist-dyeing.

② Ultraviolet Ray exposure and development.

③ Plasma etching.

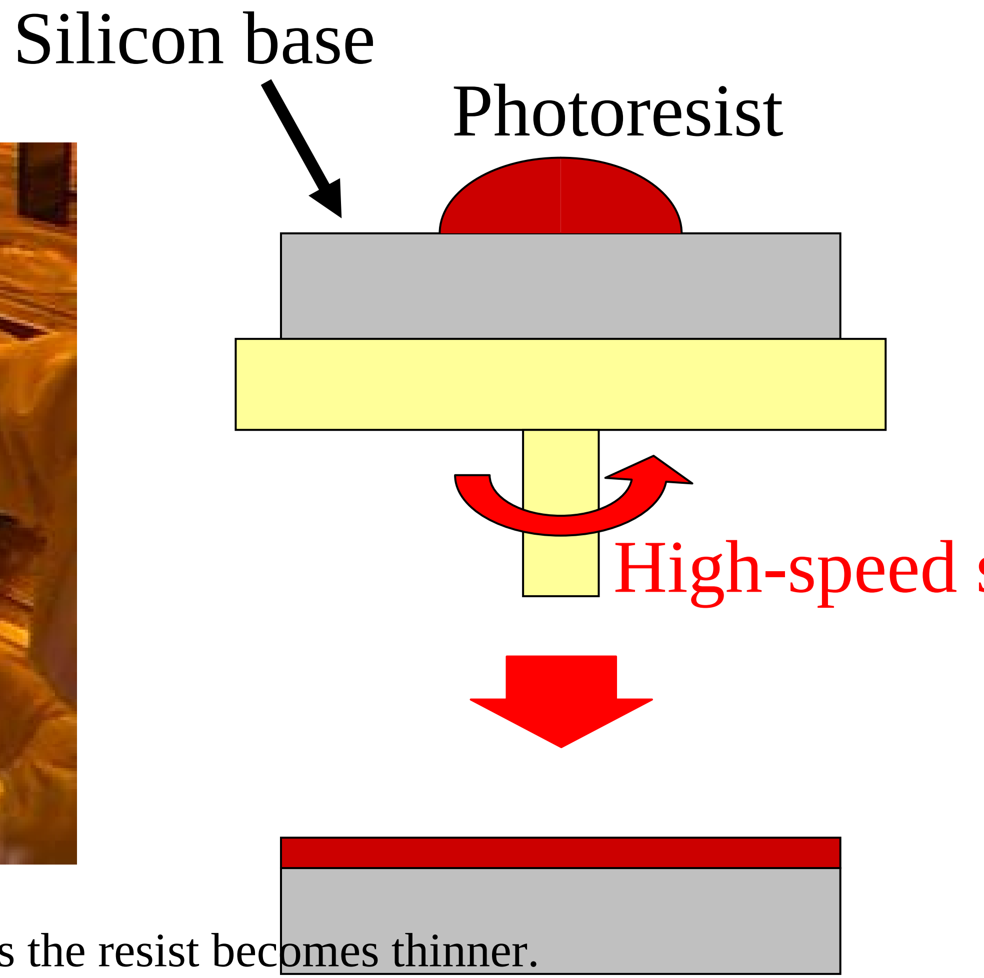
④ Resist removal.

Thin-membrane formation.

Thin-membrane formation via PVD and CVD.

Impurity distribution via ion implantation.

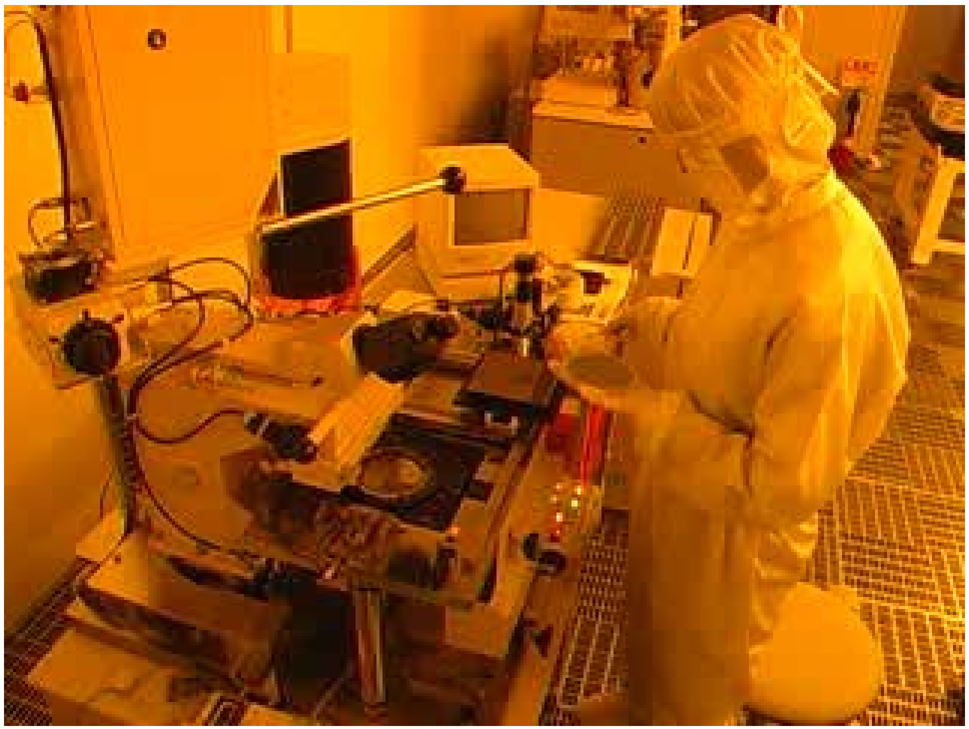
Spin-coating of Resist

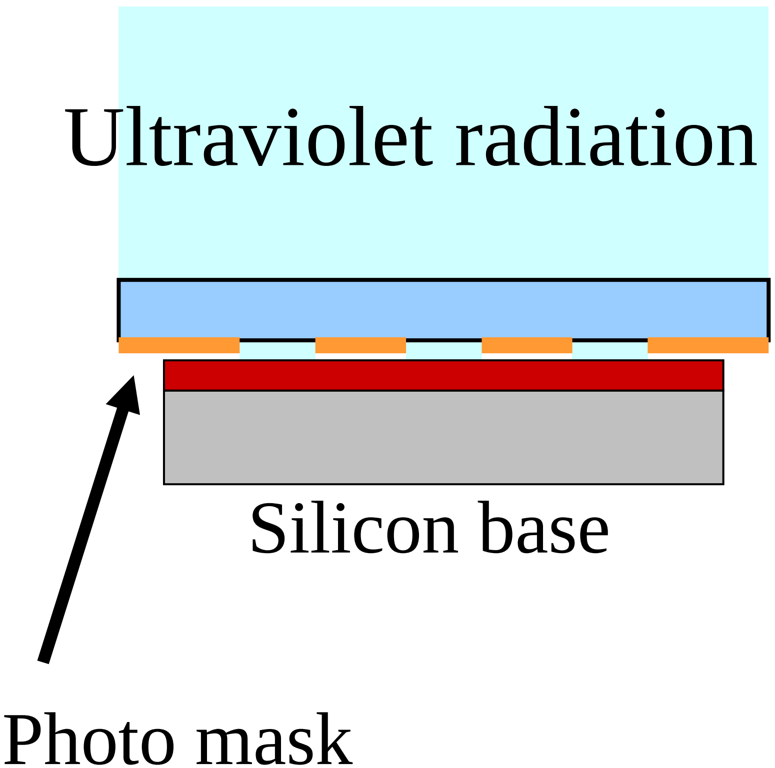


A change in interference colors is observed as the resist becomes thinner.
Starting from the spin speed of 300 per-revolution, then continue until 3,000 spins per-revolution.

Photo taken at Takeda Advanced Intellectual Building Super Clean Room, The University of Tokyo.

Ultraviolet Ray Exposure





Ultraviolet irradiation is carried out after alignment.

Photo taken at Takeda Advanced Intellectual Building Super Clean Room,
The University of Tokyo.

Development

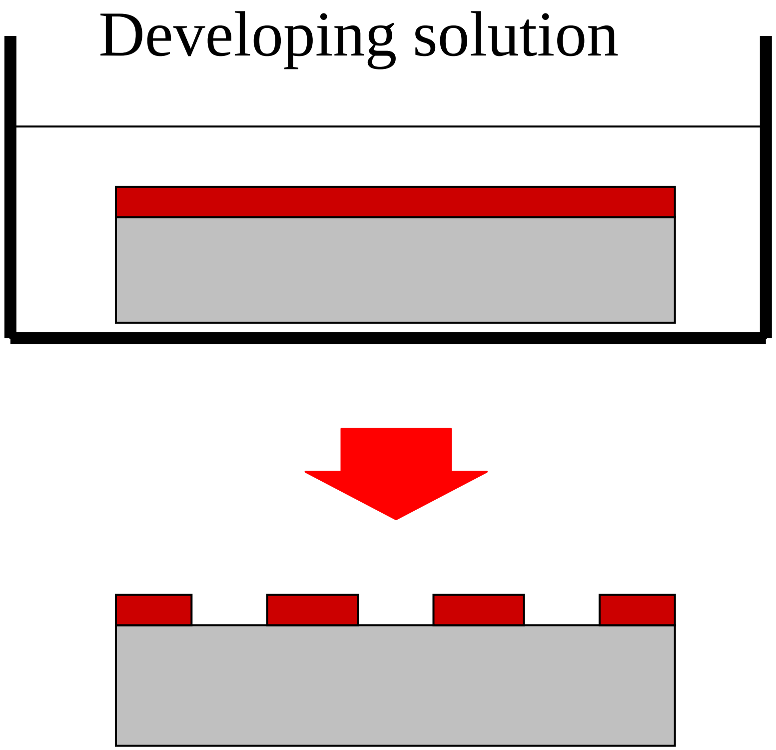
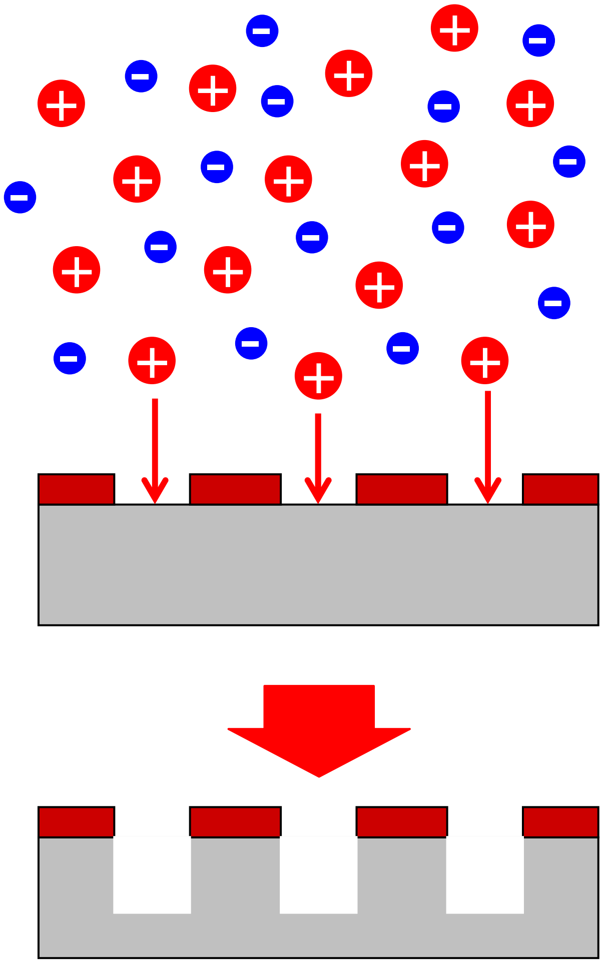


Photo taken at Takeda Advanced Intellectual Building Super Clean Room, The University of Tokyo.

Plasma Etching



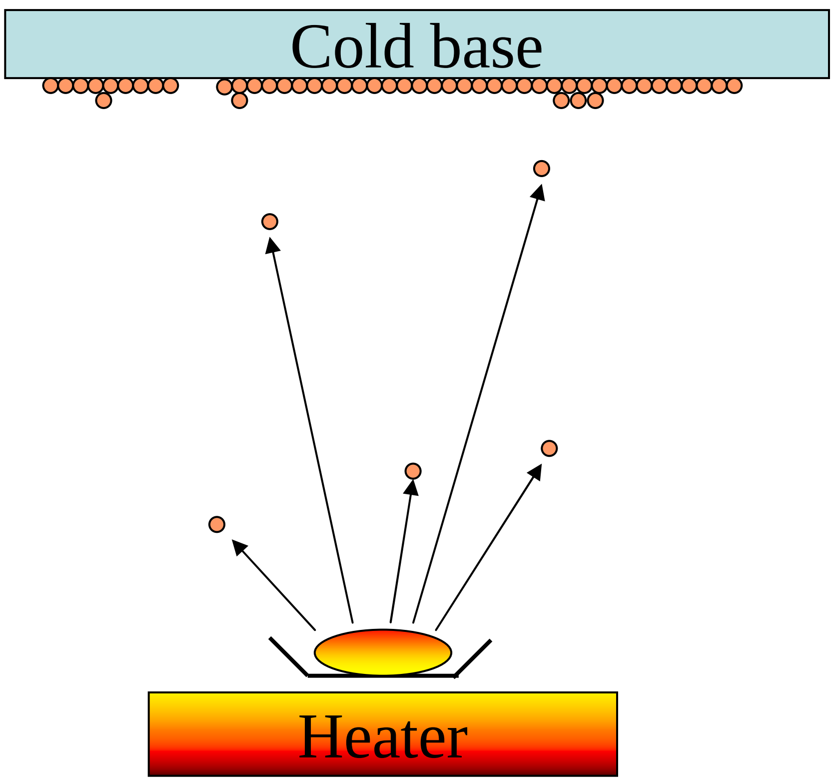
Two types of gasses (digging gas and sidewall protecting gas) are supplied alternatively; causing a color change in the plasma.

Photo taken at Takeda Advanced Intellectual Building Super Clean Room, The University of Tokyo.

Thin-membrane Forming Process

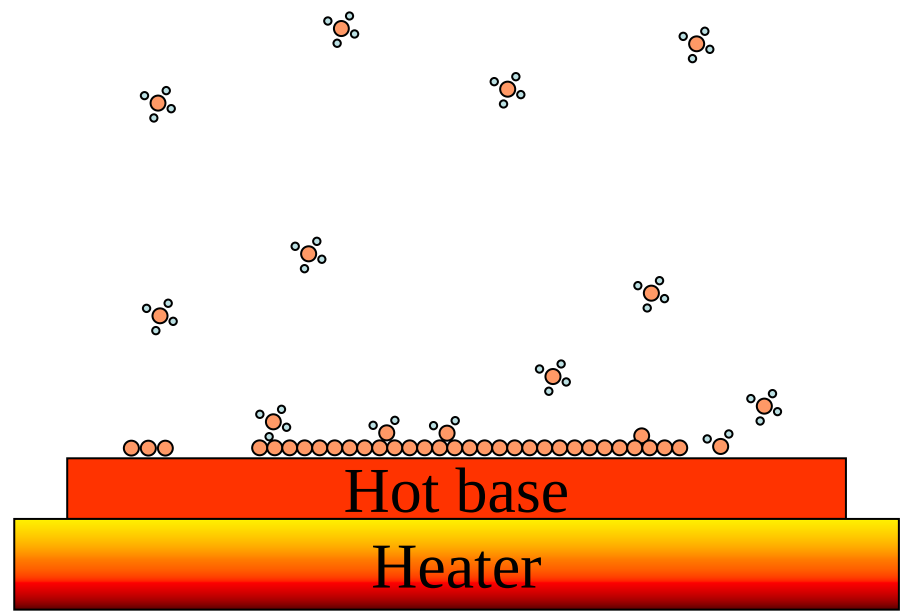
Physical Vapor Deposition

Sublimation→Atom→Solid condensation

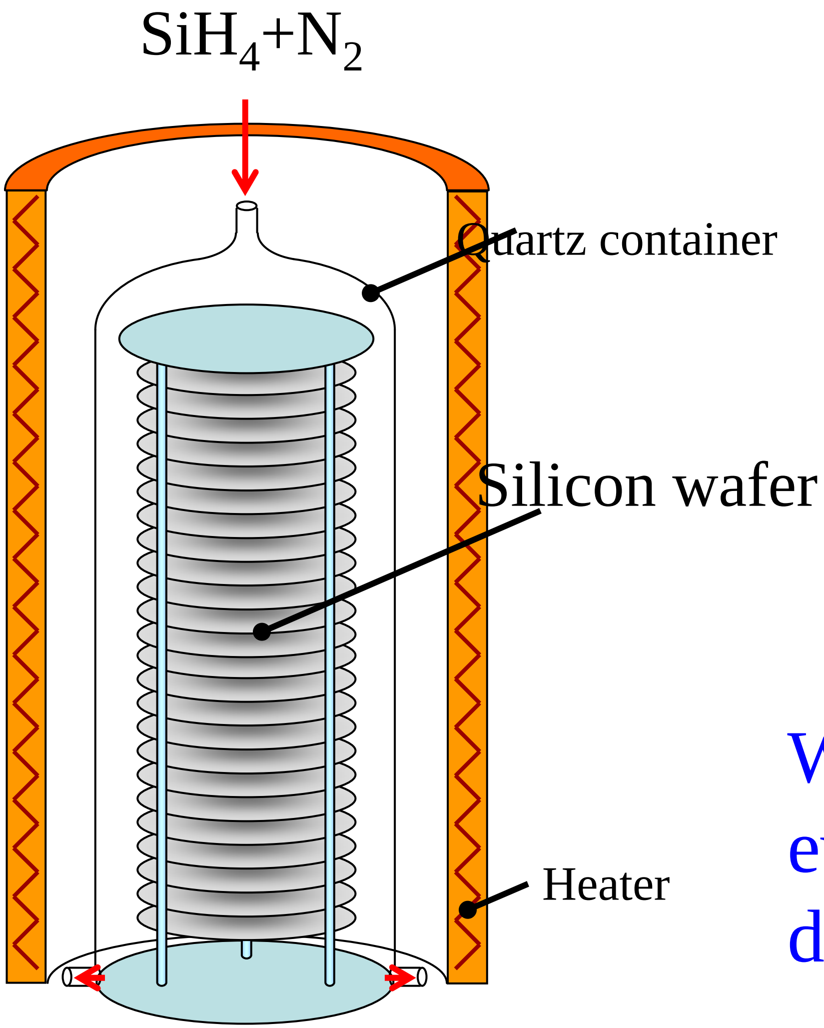


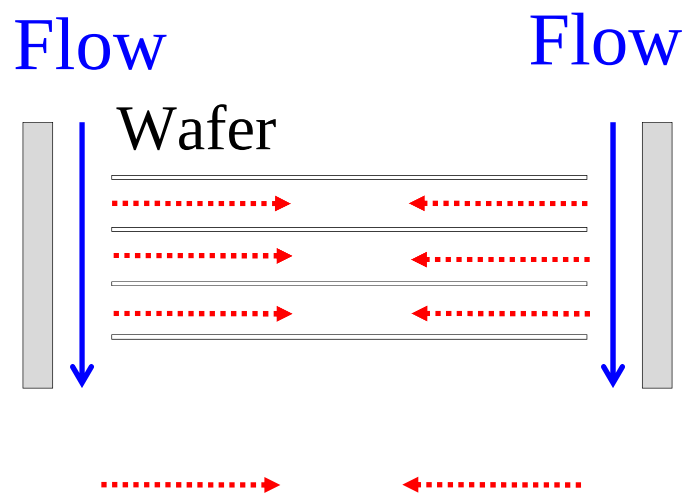
Chemical Vapor Deposition

Gas→Attachment→Surface reaction



Mass Production CVD Apparatus



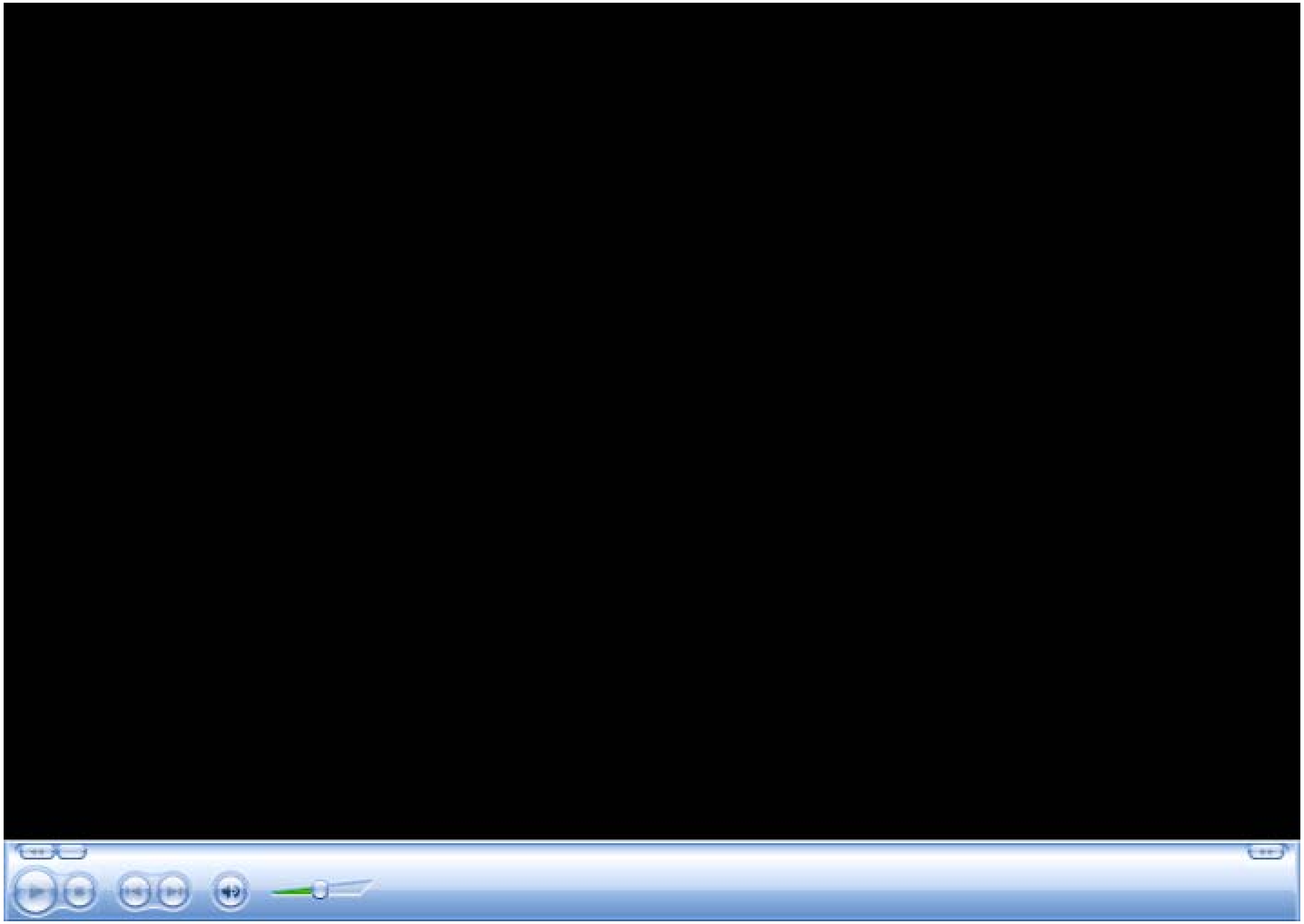


Why is a film formed
even though the mixture of gas
does not flow in?

Optical Fiber Production

- The maximal fractional index distribution toward the center of an optical fiber is compressed in the radial direction.
- Control the distribution of germanium and silicon.
- Produce the distribution via the huge Kiritanpo-(tube-shaped, half-mashed rice cake)-shaped precursor.
- Melt and pull to make the optical fiber thinner. (Spinning)
- High-purity→non-relay transmission distance.

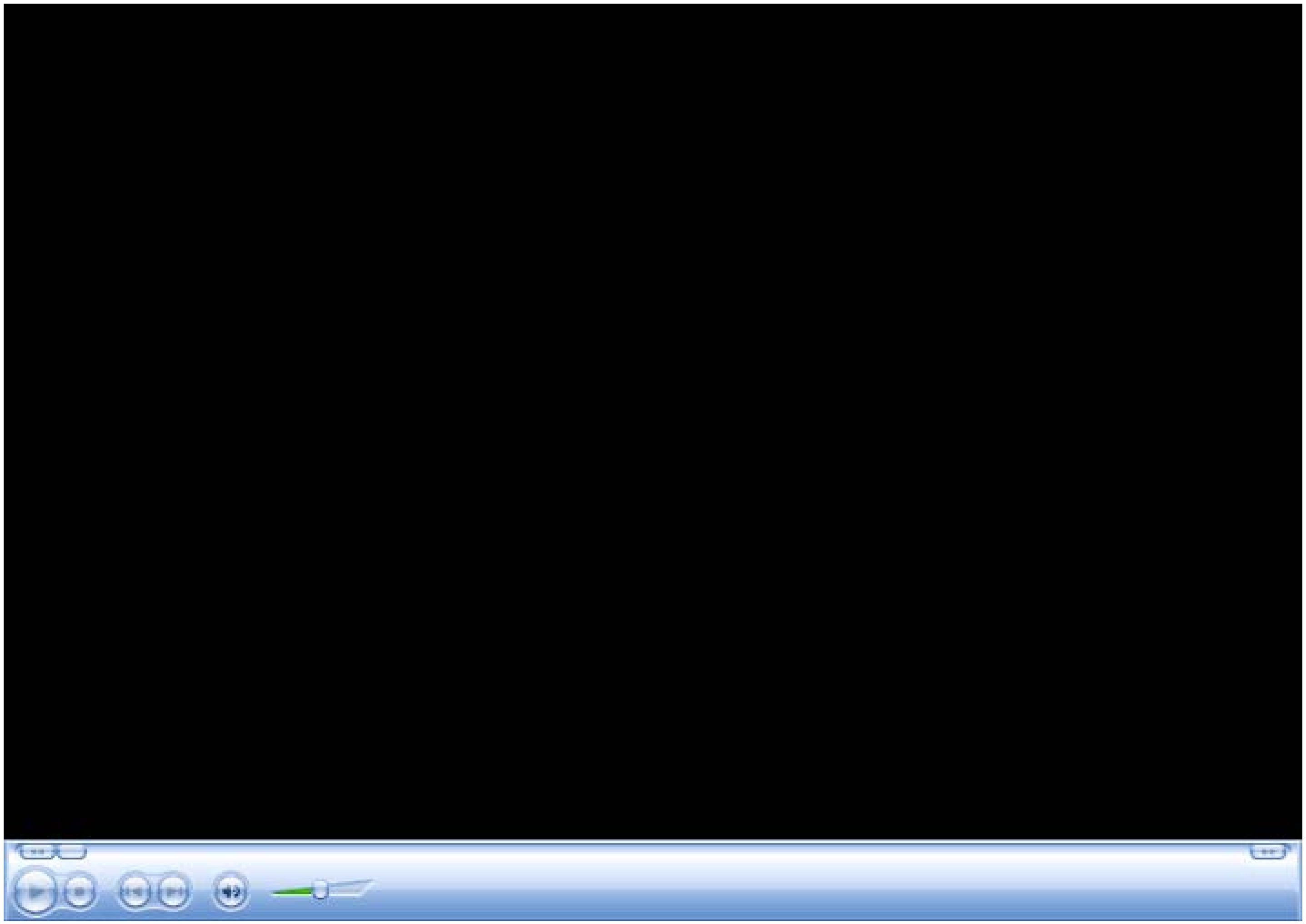
Optical Fiber Production Process



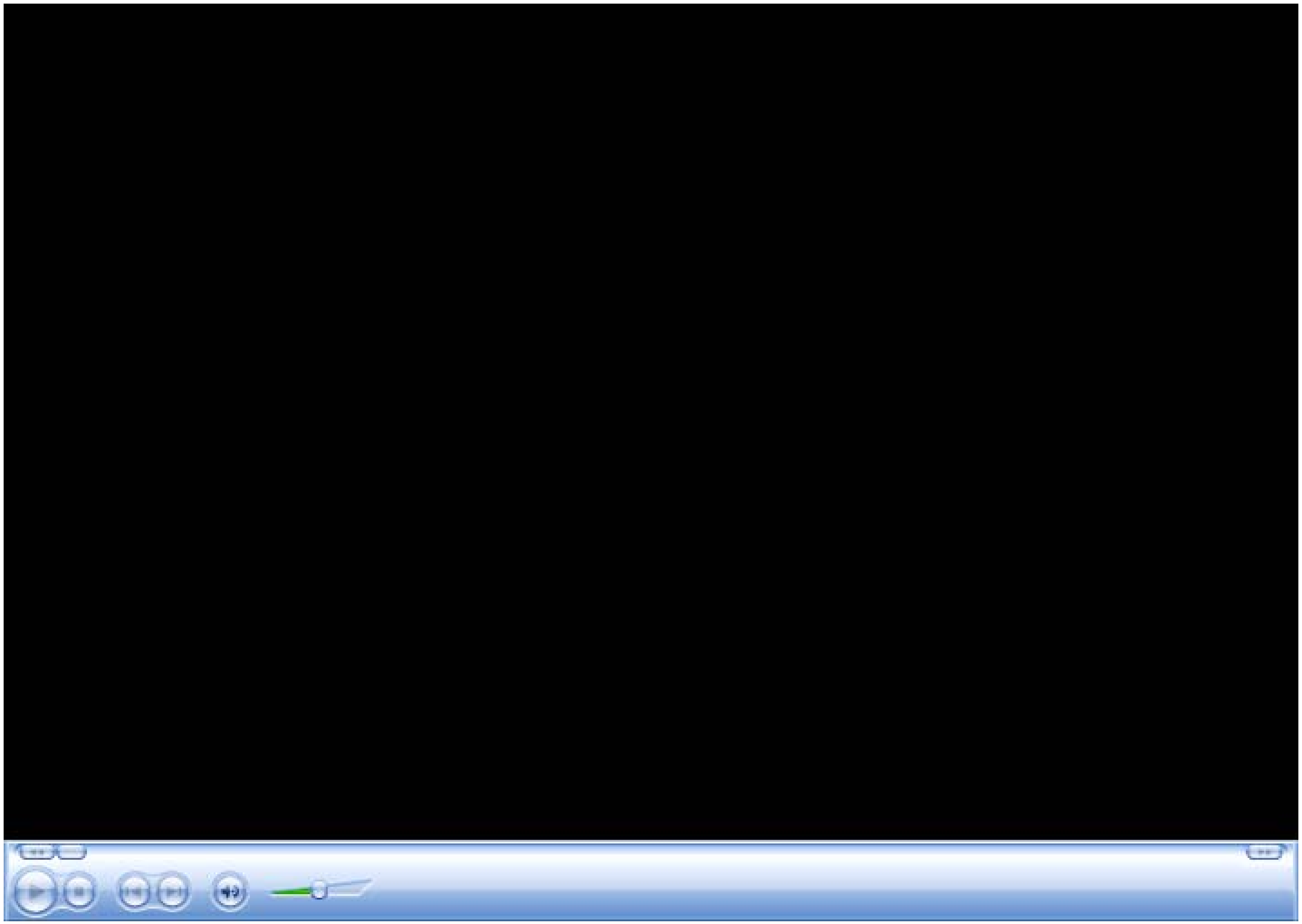
The Furukawa Electric Co., Ltd.

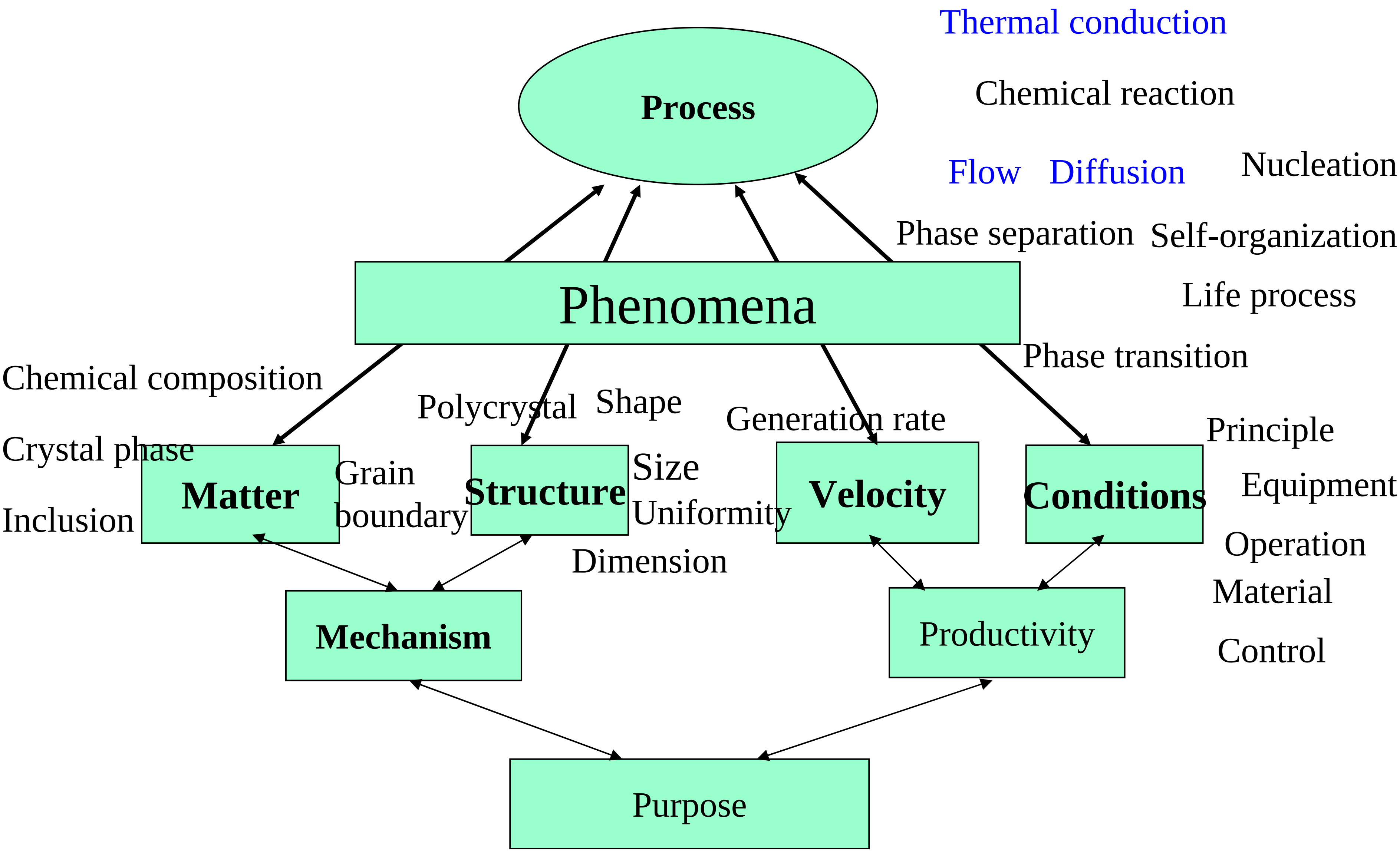
Composition of a Precursor Having an Optical Density Spectrum

‡



Spinning Process




Thermal conduction
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Principle
Crystal phase
Grain boundary
Size
Uniformity
Equipment
Matter
Structure
Velocity
Conditions
Inclusion
Dimension
Operation
Material
Mechanism
Productivity
Control
Purpose

Development (Flow and Diffusion)

- Monocrystal pulling
  - ✓ Using a seed crystal.
  - ✓ No nucleation occurs.
  - ✓ Complete Temperature control.
  - ✓ Makes the flow calm.

Flow: Laminar Flow and Turbulent Flow

- Laminar flow
  - ✓ The streamline can be followed.
- Turbulent flow
  - ✓ The flow has an eddy current.
  - ✓ The streamline cannot be followed.

Figure removed due to copyright restrictions

$$\mathrm{Re} = \frac{d v \rho}{\mu}$$

d : characteristics length

v : flow rate

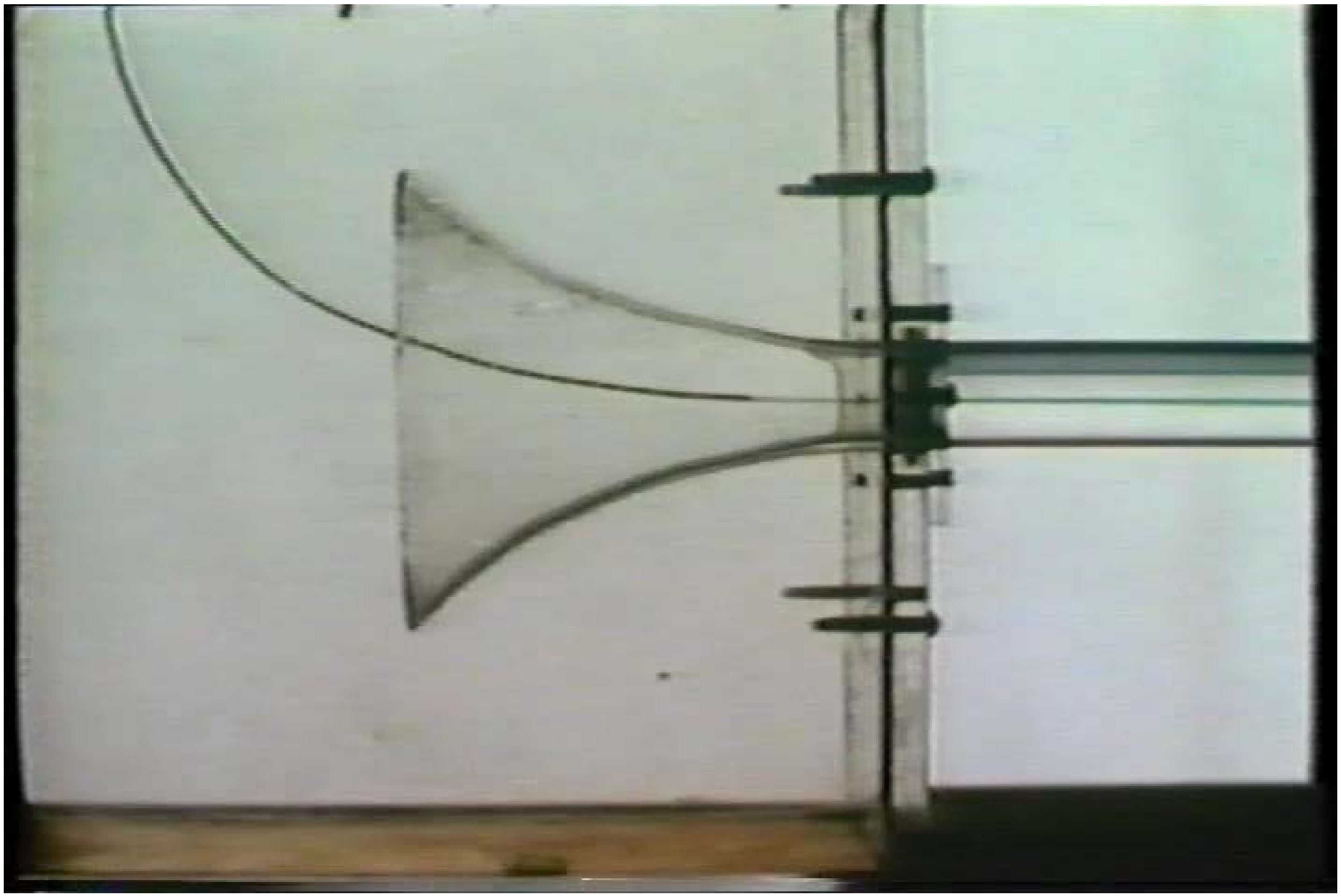
r : flow density

m : viscosity coefficient

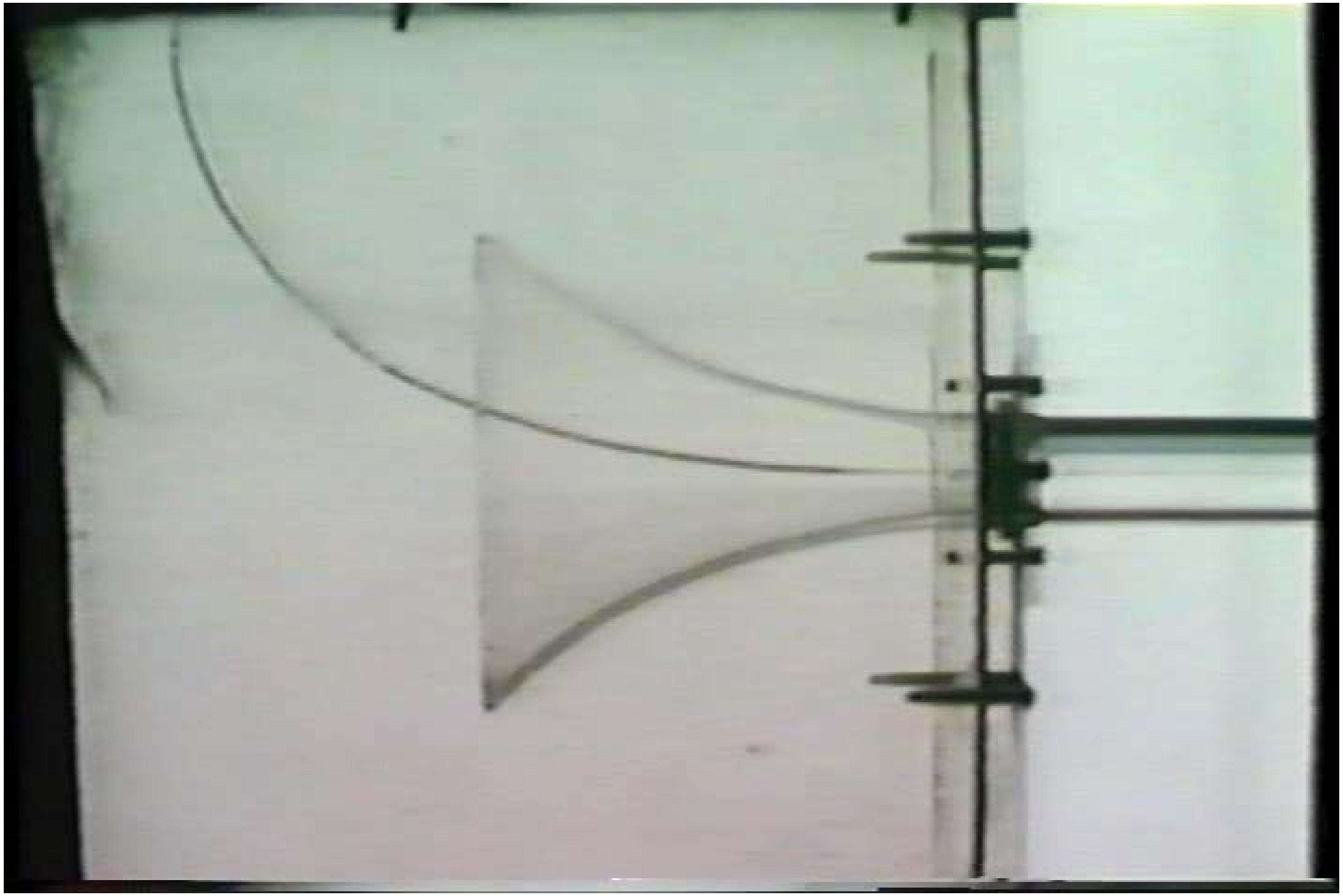
Adding Milk After Stirring Slowly

Adding Milk After Stirring Intensely

The Mix of Turbulent Flows: Blends in Well



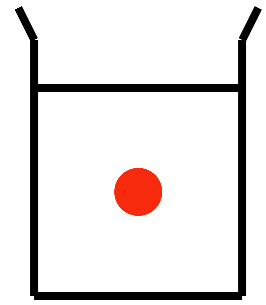
Laminar Flow: Does Not Blend In



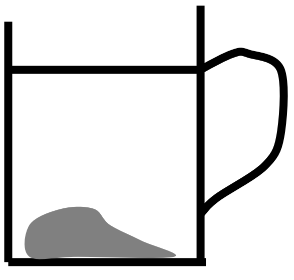
Getting a Sense of Diffusion

Liquid phase diffusion and vapor phase diffusion.

A smudge appearing in the ink-dripped water.

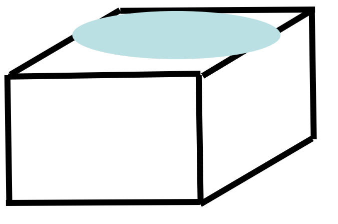


A lump of sugar left without stirring.

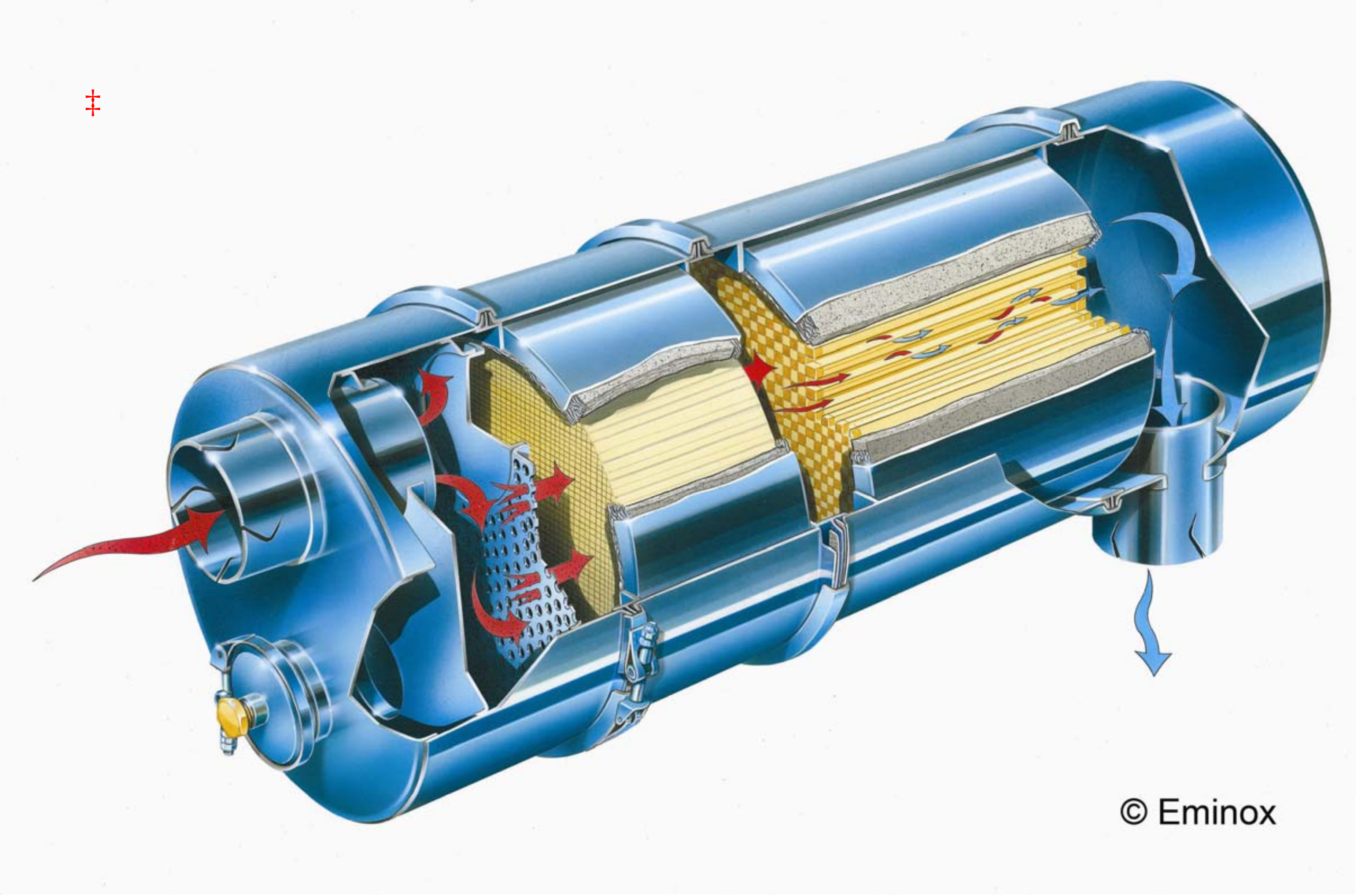


Sugar sprinkled on ice.

E.g., frozen strawberry.



Honeycomb-type Catalytic Reactor



Eminox Continuously Regenerating Trap (CRT®) System

http://www.eminox.com/products/crt.shtml

A Vapor Phase Performs Fast Diffusion

An automobile exhaust purification catalyst.

Honeycomb type.

Traveling inside the five millimeter tube by the speed of one hundred meters per-second.

Every atom is in contact with the catalysts on the wall.

Small talk:

The impurity atoms contained in a glass of pure water:

There is one impurity atom (electron) for every nanodot.

The Identity of Diffusion

The uniform state obtained by the exchange of atoms.

Air (vapor)

Six billion collisions per-second at every 0.1 micron
with a traveling speed of four hundred meters per-second.

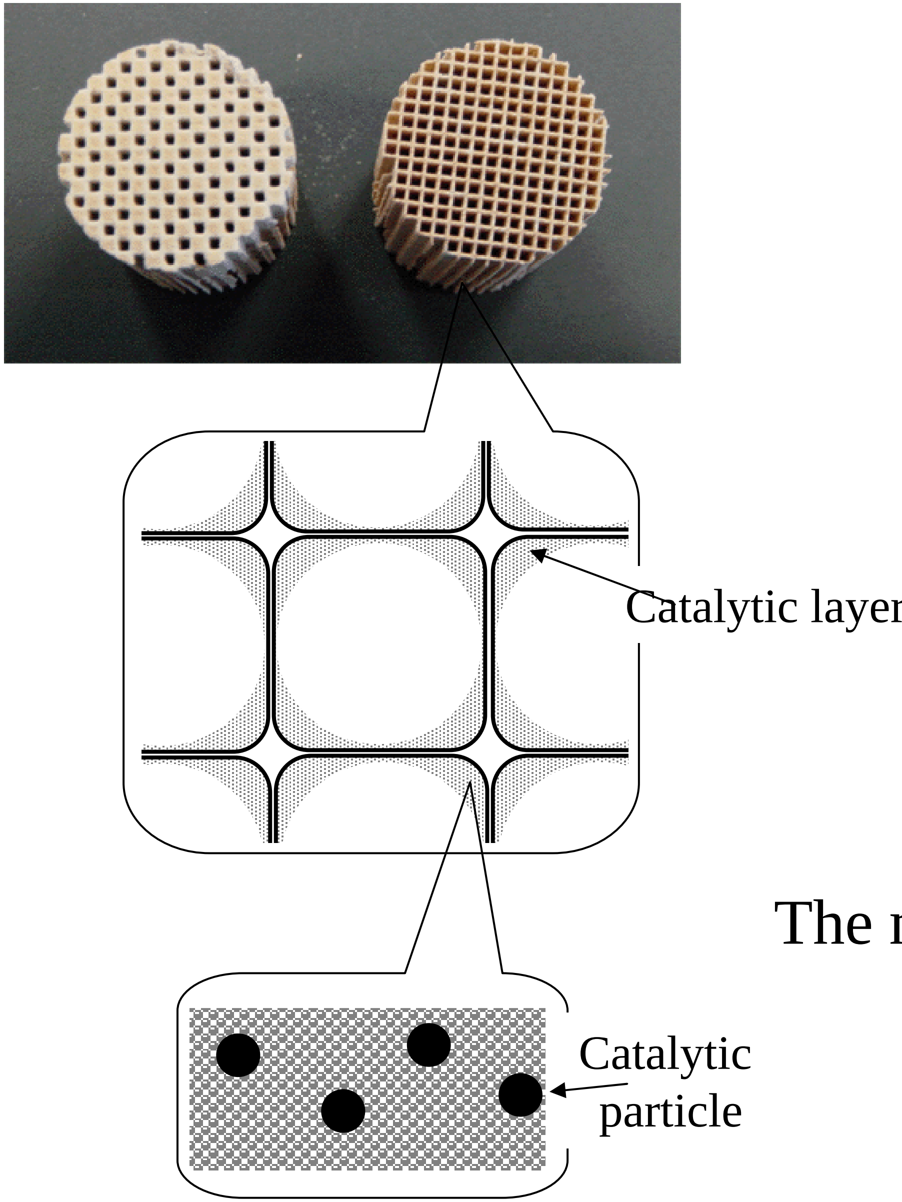
Water (liquid)

Traveling with the speed of four hundred meters per-second;
however,
in a congested state.

Ice (solid)

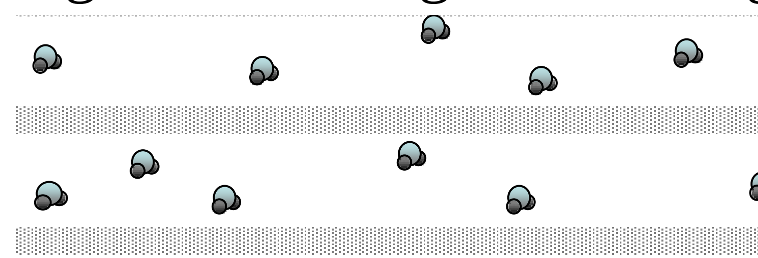
Oscillation occurs, but atoms are basically fixed.

Honeycomb-type monolith catalysts

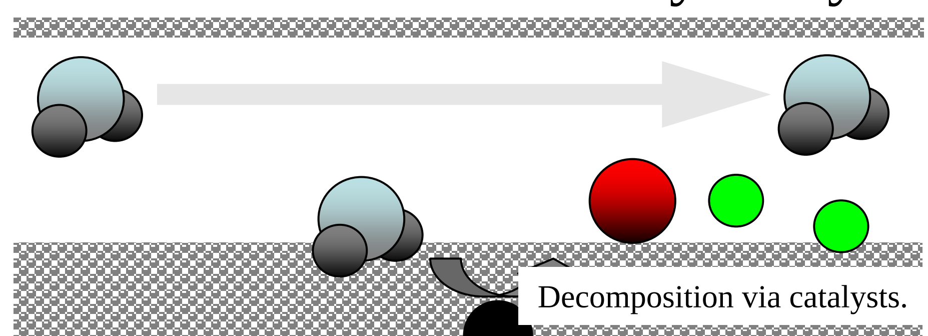


mm order
Huge amount of gas is flowing.

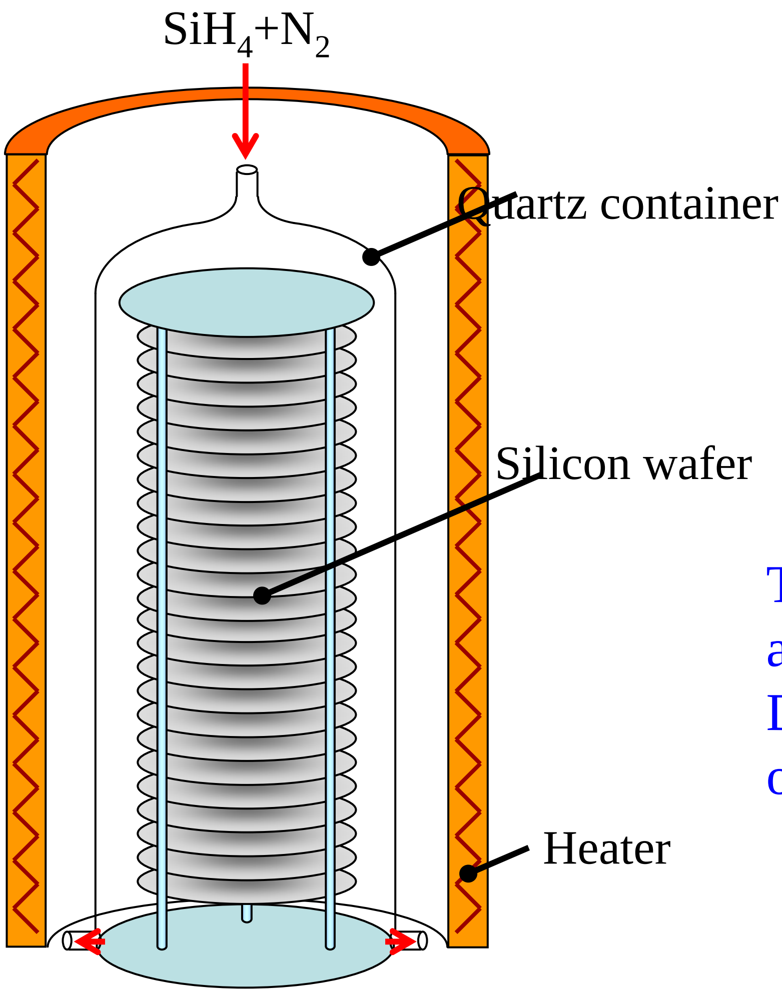
µm order
Huge amount of gas is flowing.

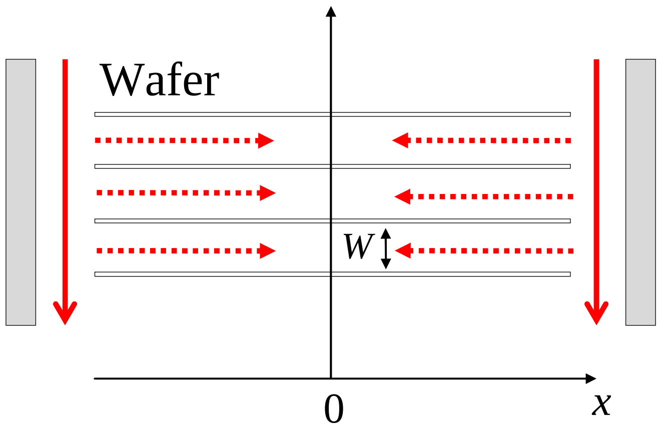


nm order
The molecules diffuse the catalytic layers.



Diffusion is Necessary for Film Production

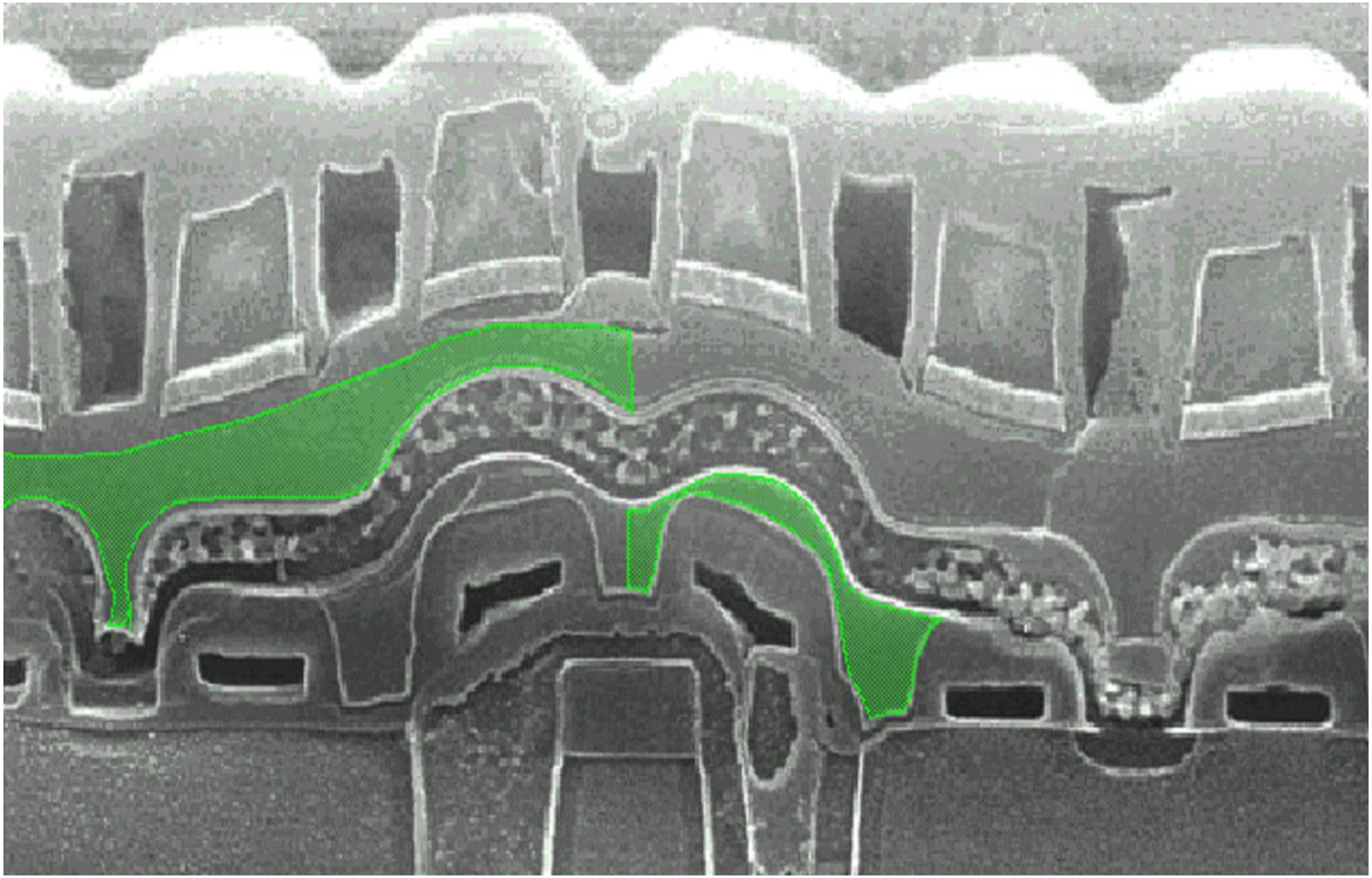




The mixture of gas is carried into the apparatus by flow.
Diffusion further carries the gas onto the wafer surface.

Cross Section of a Device

‡

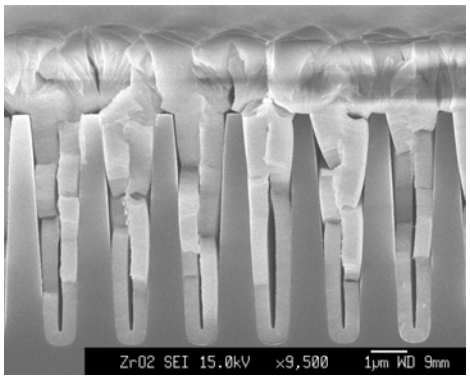


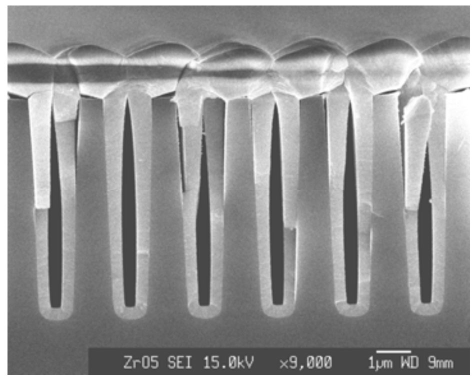
Katsuro Sugawara, Hiroshi Fukuda (1995) “Super LSI Processing”

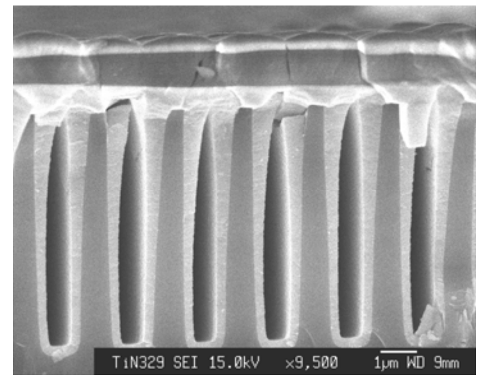
Baifukan, Chart4.6

Step Coverage

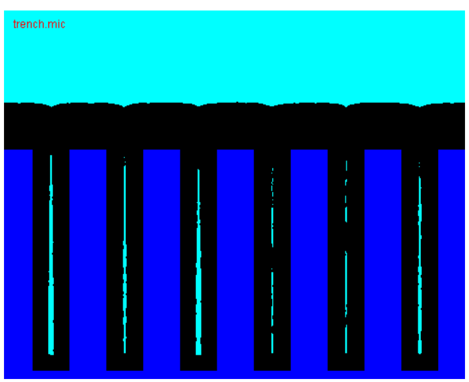
The gaps can be filled out if the step coverage conditions of the oxide film formation (CVD method) is adjusted.

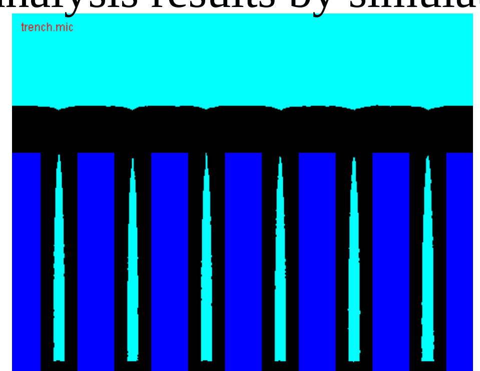


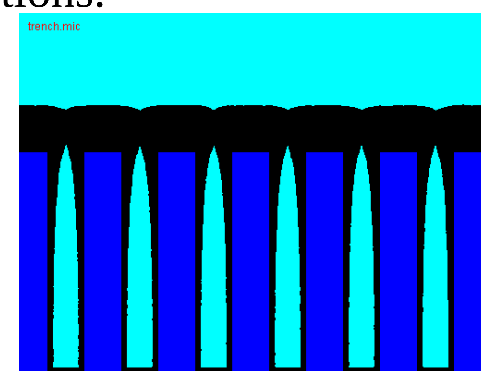




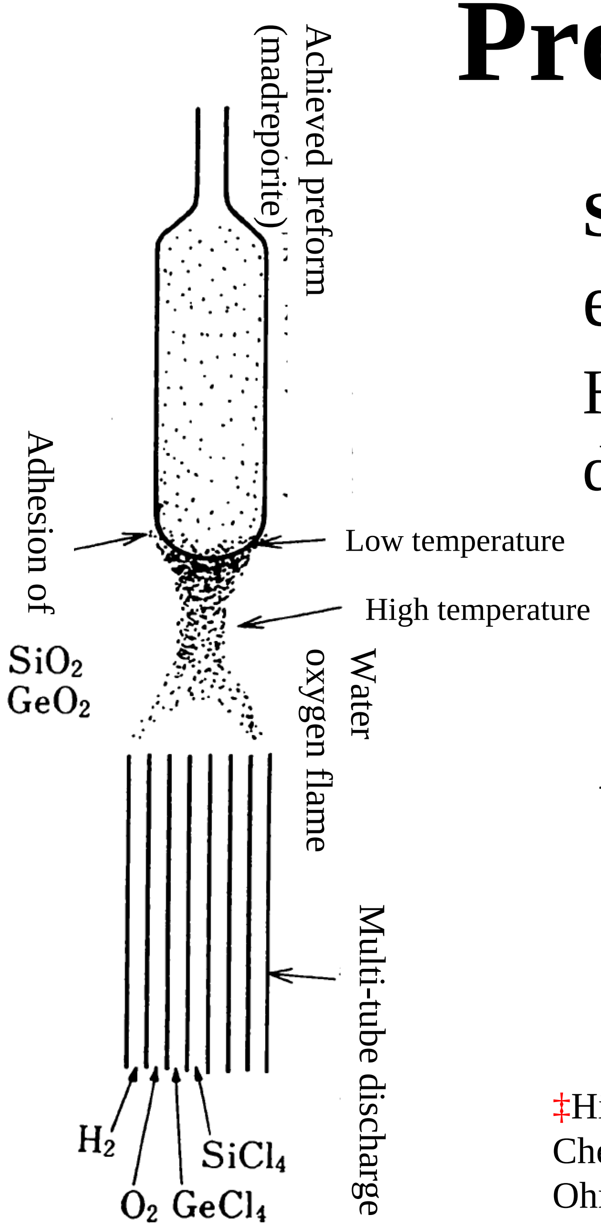
The analysis results by simulations.







Composition of Optical Fiber Precursor



SiO_2 exists in the core and **GeO_2** exists outside.

High-speed reaction generates particles: diffusion control

$SiCl_4 + 2H_2O \rightarrow SiO_2 + 4HCl$

$GeCl_4 + 2H_2O \rightarrow GeO_2 + 4HCl$

A quadruplet tube.

Tetrachlorosilane is found in the core.

Germaniumtetrachlorid is found outside.

Water and oxygen exist outside.

‡Hiroshi Komiyama, Kensaku Mizoguchi 1994 “New System Chemical Engineering Functional Materials Process Engineering”, Ohmsha, Ltd., P103, Chart5･13

Examples of Diffusion Utilization and Control

	Utilization	Control
Vapor phase	**Film formation apparatus** **Honeycomb catalyst**	**Optical fiber (particle formation by high-speed reaction)**
	High-purification: gas or liquid phase	
Liquid phase	**Liquid phase reaction (Stir: diffusion at atomic level)**	**Multi-layer film forming (high-speed pulling)**
Solid phase	**Doping** **Optical fiber (smooth distribution)**	**Akashi fiber (alloying)**

Control of Wafer Diameter by Heat Balance

The heat balance of an ingot.

$$\pi r^2\left(\kappa\frac{dT}{dz}+v\rho Q\right)=2\pi rLF_Q$$

Thermal conduction Latent heat = Emission

$$r=\frac{2LF_Q}{\kappa\frac{dT}{dz}+v\rho Q}$$

r, L：silicon crystal radius, length
k：heat conductivity
v:pulling speed
r：silicon density
Q：latent heat of freezing
F_Q：heat radiation flux from silico

Controlled by pulling speed and temperature distribution.

What Are the Practical Uses of a 400mm Wafer?

Examples of Semiconductor Production Cost

① Plant and equipment investment required to manufacture （monthly production 10 thousand wafers)

Assume an investment of 150 billion yen and a plan for ten years production (1.2 million wafers).

150 billion yen÷1.2 million wafers＝125,000 yen/wafer

② Process cost（per single wafer)

200 yen/process×600 process＝120,000 yen/wafer：CPU

200 yen/process×200 process＝ 40,000 yen/wafer：DRAM

③ Wafer cost

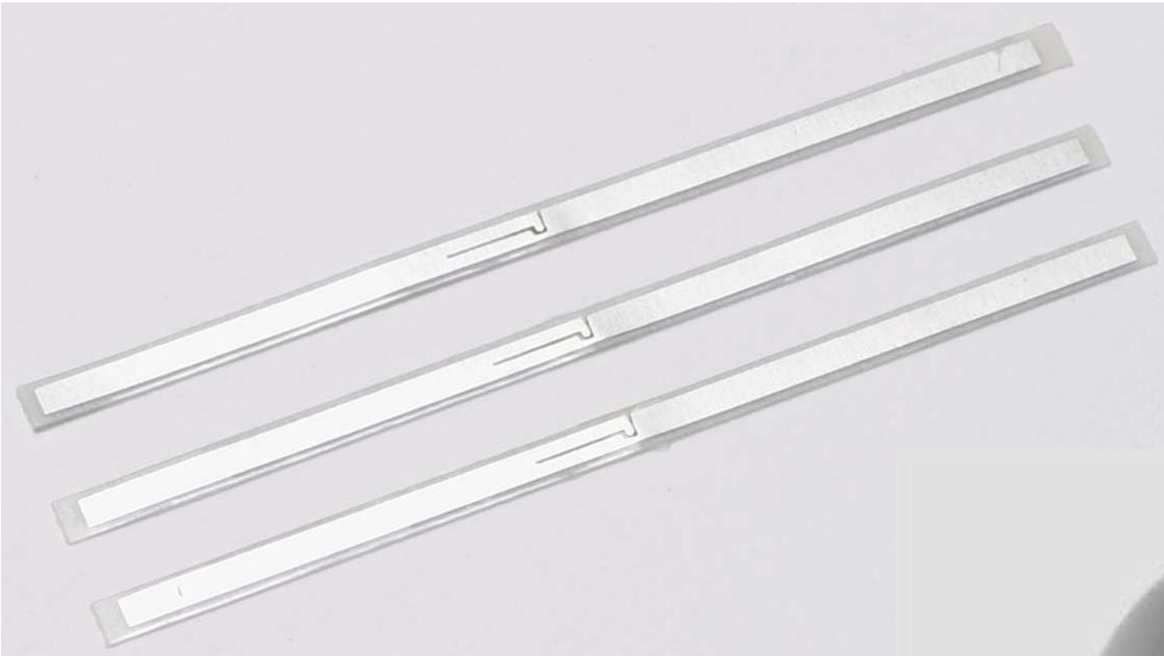
30,000 yen/wafer

④ Chip unit price（1,000 chips/wafer)

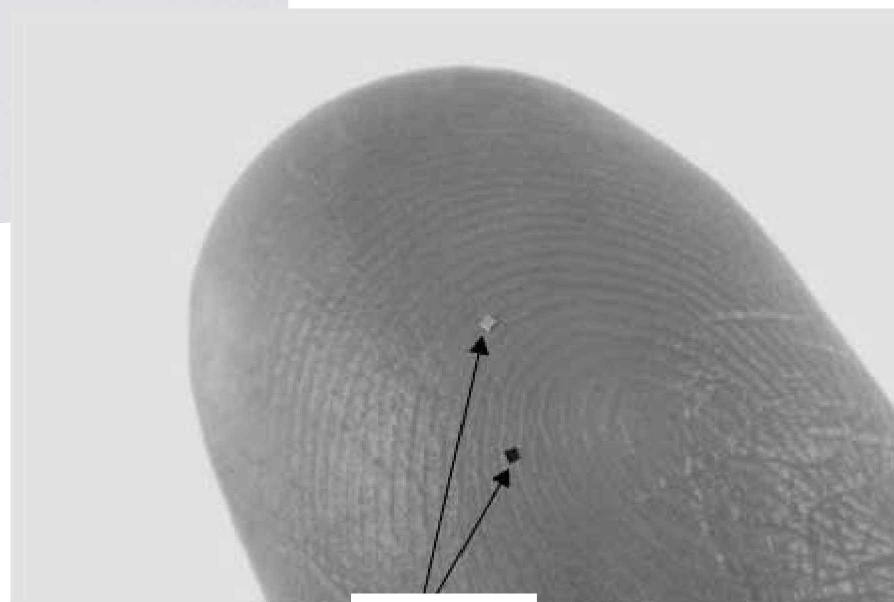
275,000 yen/wafer＝275 yen/chip：CPU

195,000 yen/wafer＝195 yen/chip：DRAM

RF Devices: Mu-chip

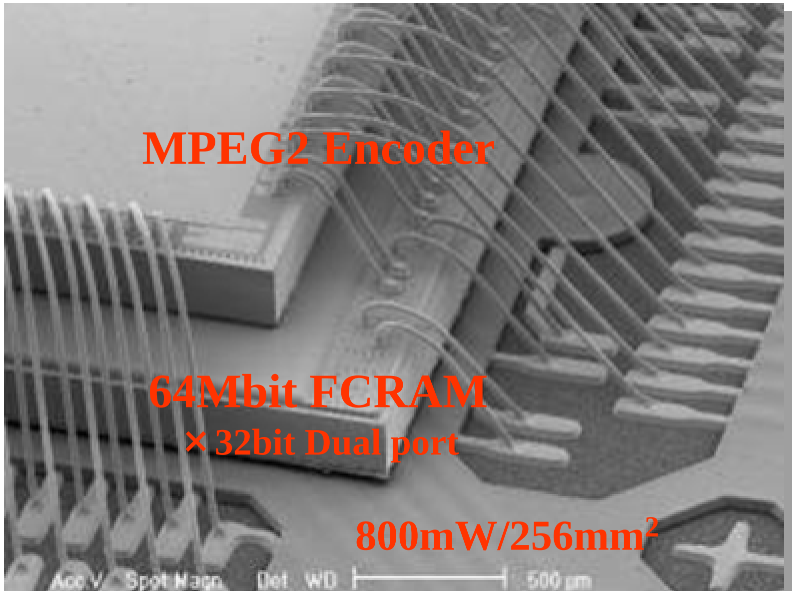


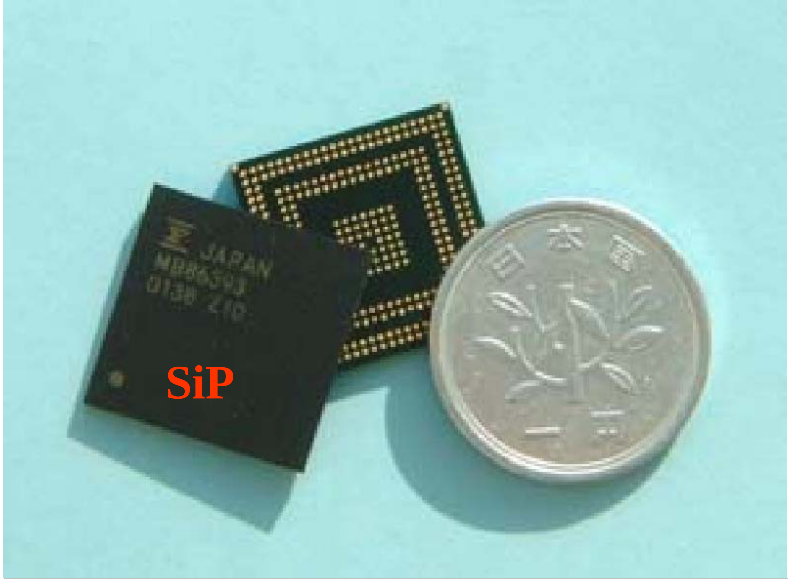
‡「μ-Chip」Hitachi, Ltd.



The mu-chip was inserted in the tickets used by the Aichi International Exposition during printing.

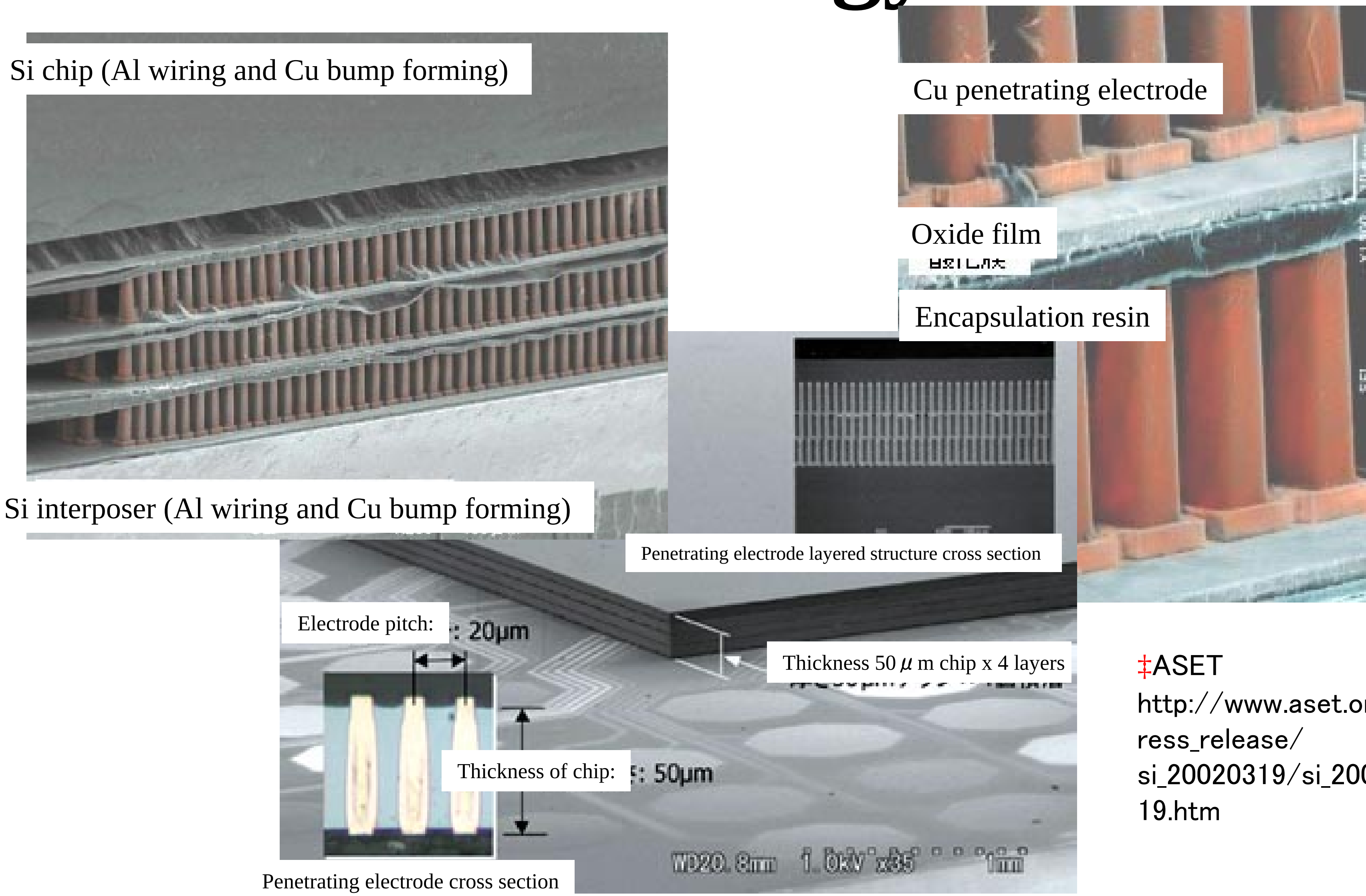
SiP Devices





‡FUJITSU
http://pr.fujitsu.com/jp/news/2001/11/20.htm

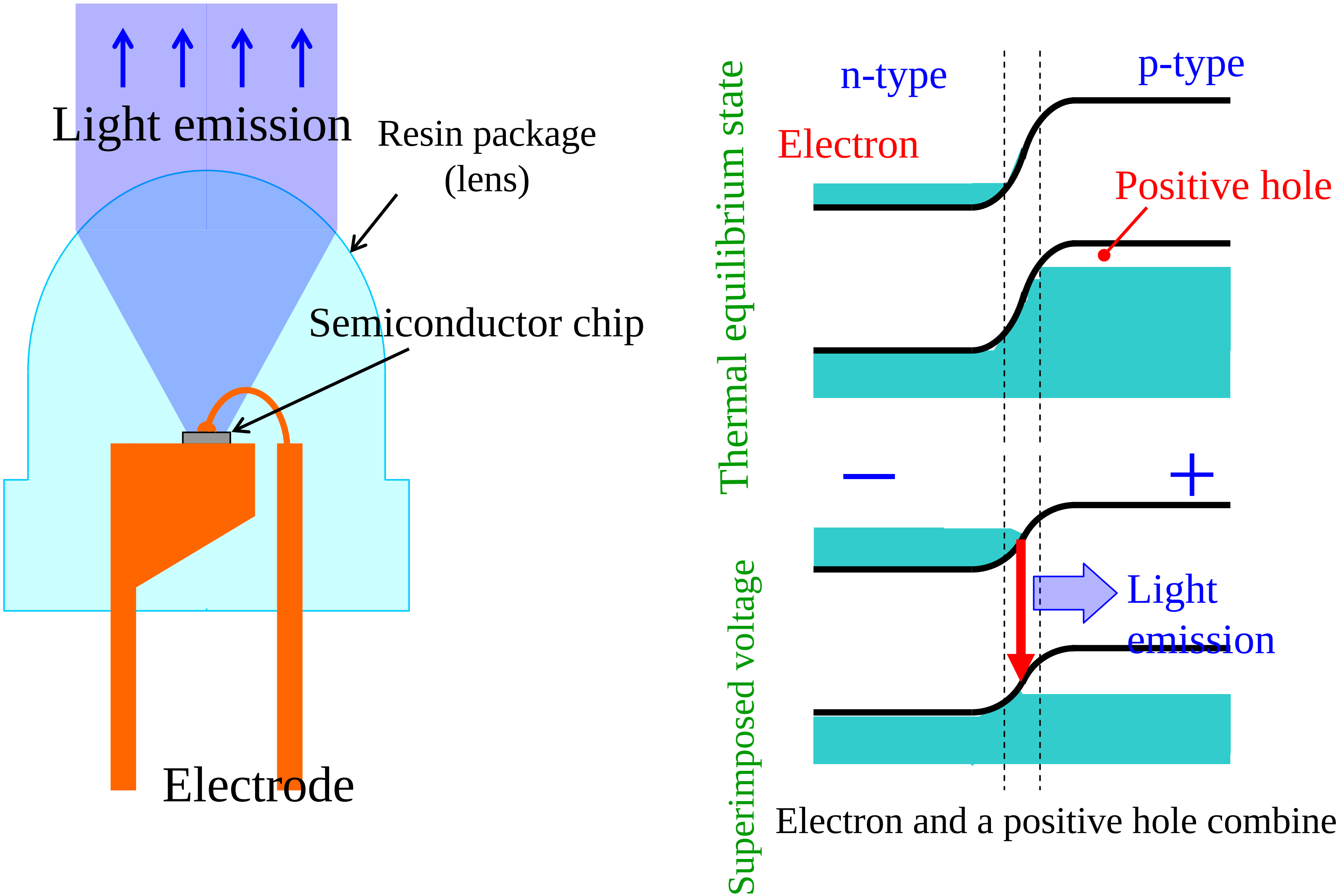
Three-dimensional Packaging Technology



‡ASET
http://www.aset.or.jp/press_release/si_20020319/si_20020319.htm

Mechanism and Structure of LEDs

The electrons and positive hole do not pile up on each other.

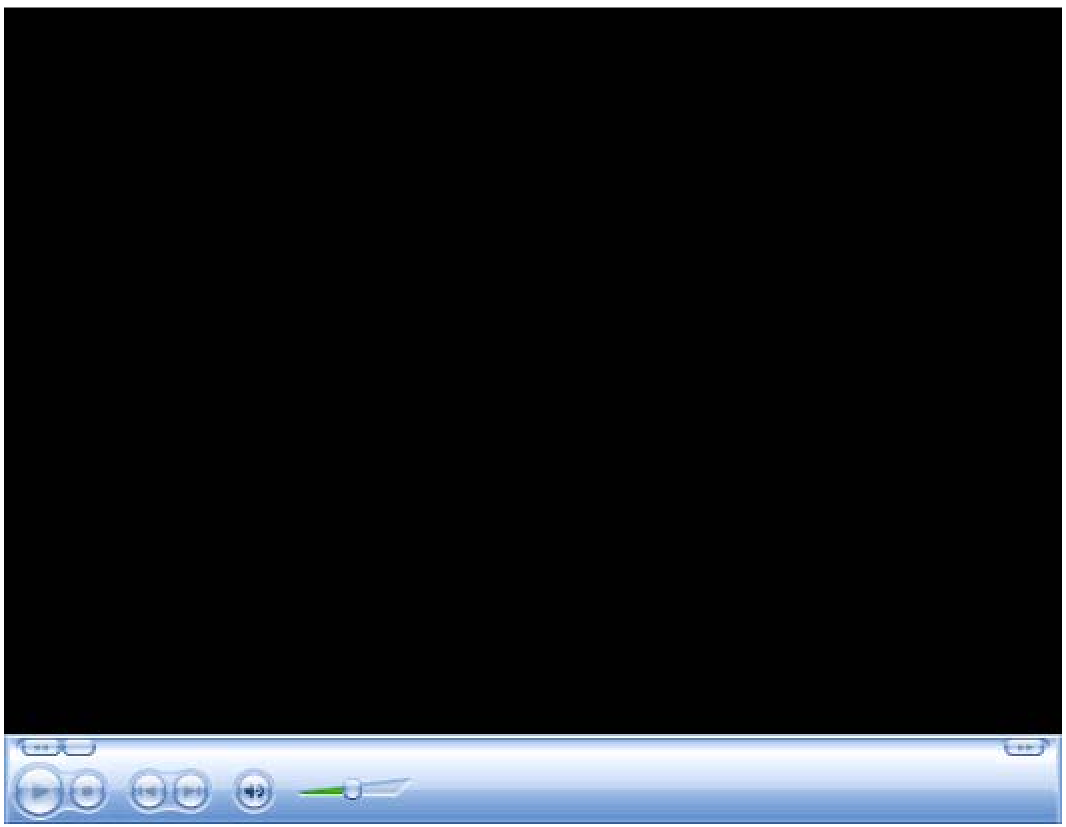


Electron and a positive hole combine.

Studies of LEDs at University Facilities

- GaN thin film deposited using the metal-organic vapor phase epitaxial growth (CVD method).
- Deposition of electrode material (PVD method).
- The emission of light by a completed blue LED.

Metal-organic Vapor-phase Epitaxial Growth



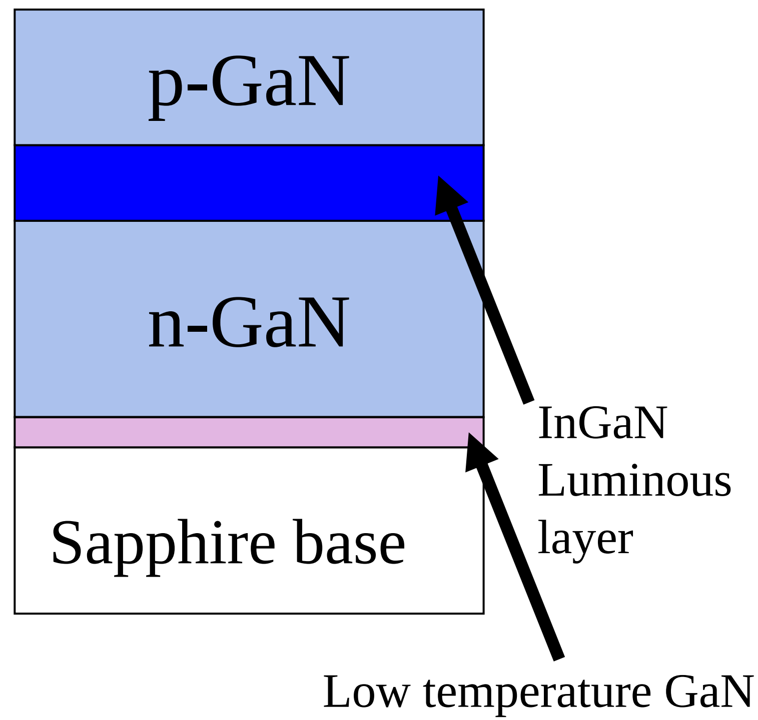
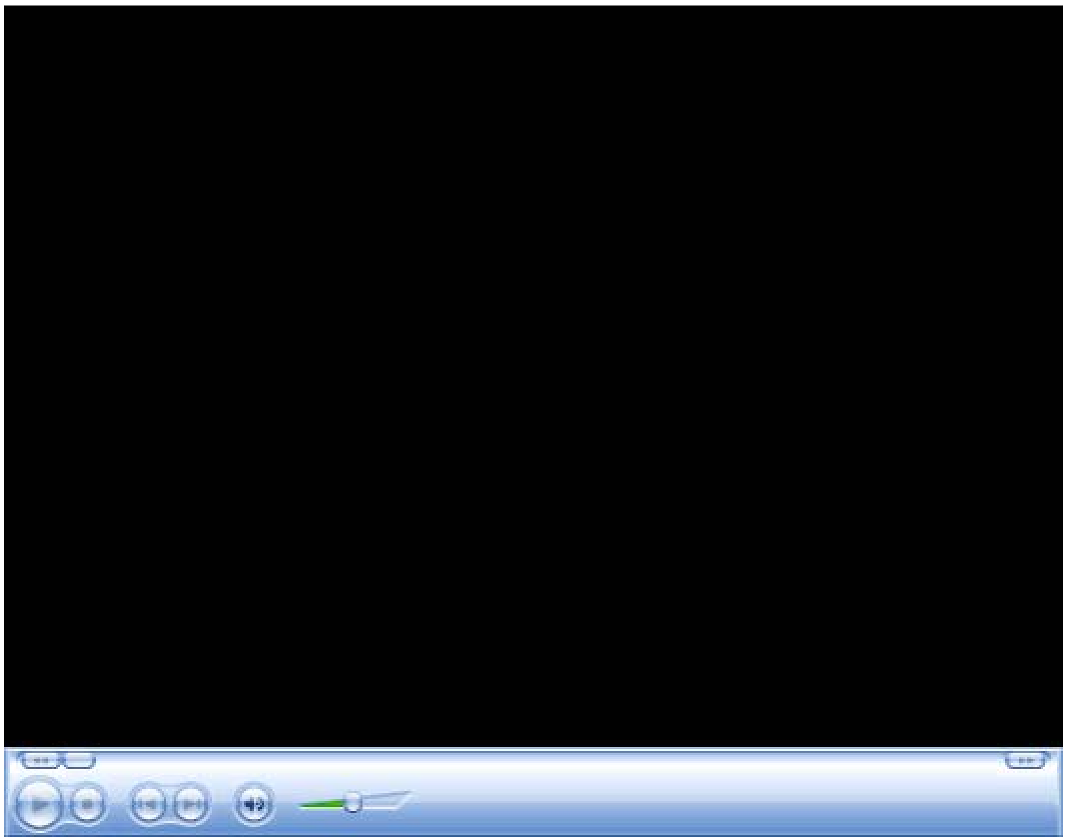


Photo taken at Nakano and Sugiyama Laboratory,
Department of Electrical Engineering, The University of Tokyo.

Blue Luminescence Measurement



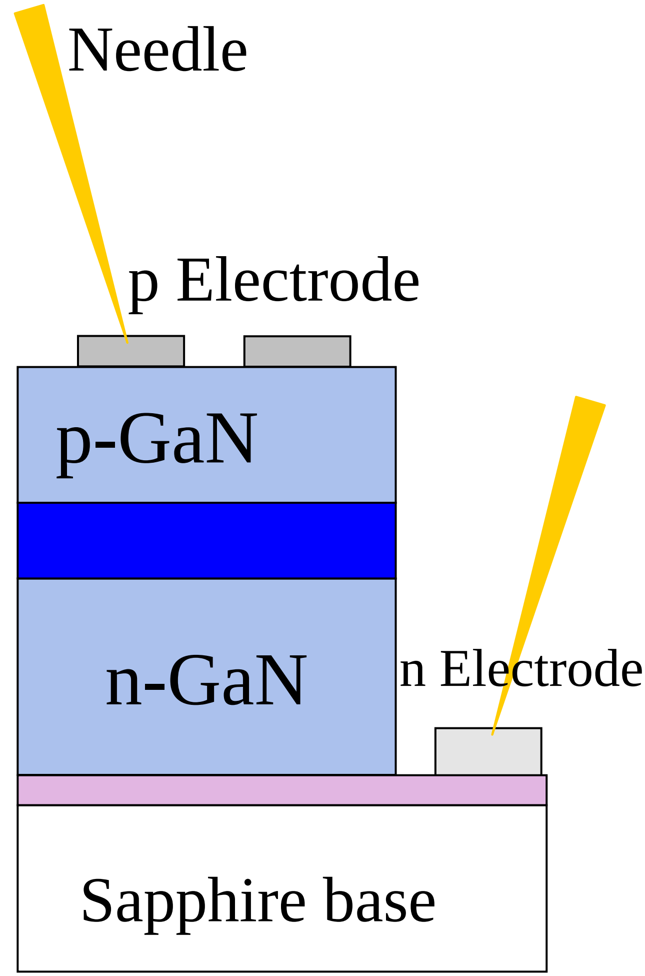


Photo taken at Takeda Advanced Intellectual Building, Electric Engineering Laboratory, The University of Tokyo.

Experiments Dealing With Future Technology

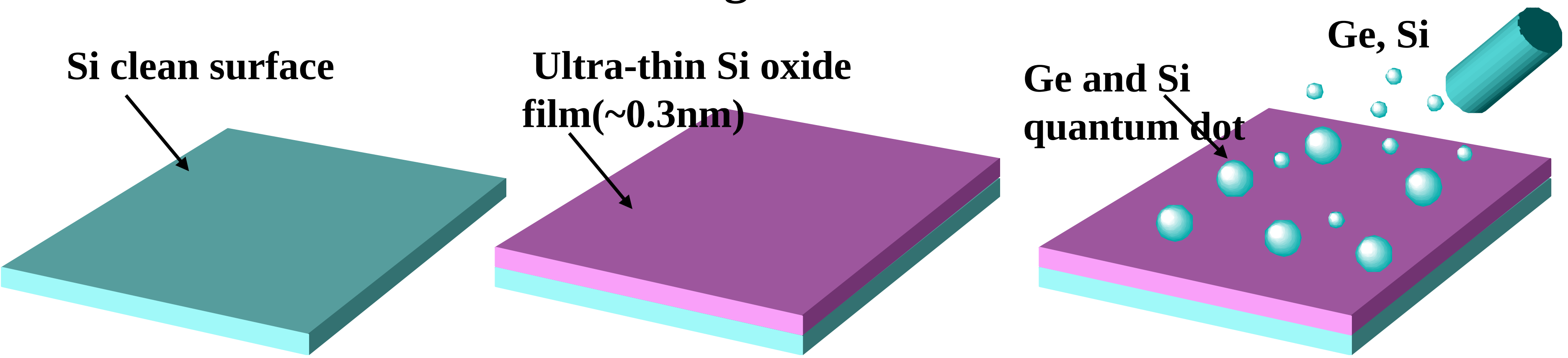
E.g., light and electrons, quantum devices, and self-organization.

Independent Growth Method for Quantum Dots in Ge and Si

(1) Si clean surface forming.

(2) Ultra-thin Si oxide film growth.

(3) Ge and Si quantum dot growth.



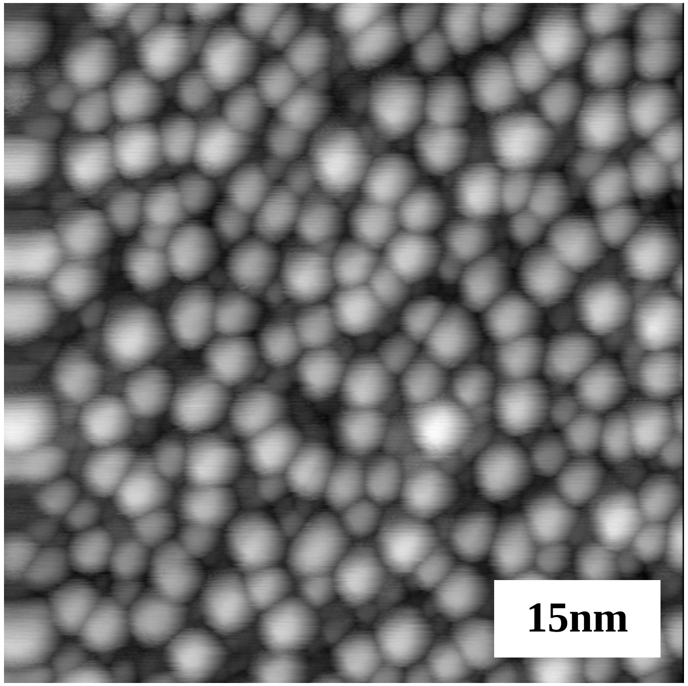
1250°C heating

Oxidation : 600°C,10min
$2x10^{-4}$Pa (O_2)

Ge deposition : 450-500 °C
1.8-2.5 thickness atomic layer.

Independent Growing Ge and Si Quantum Dots on Ultra-thin Si Oxide Film

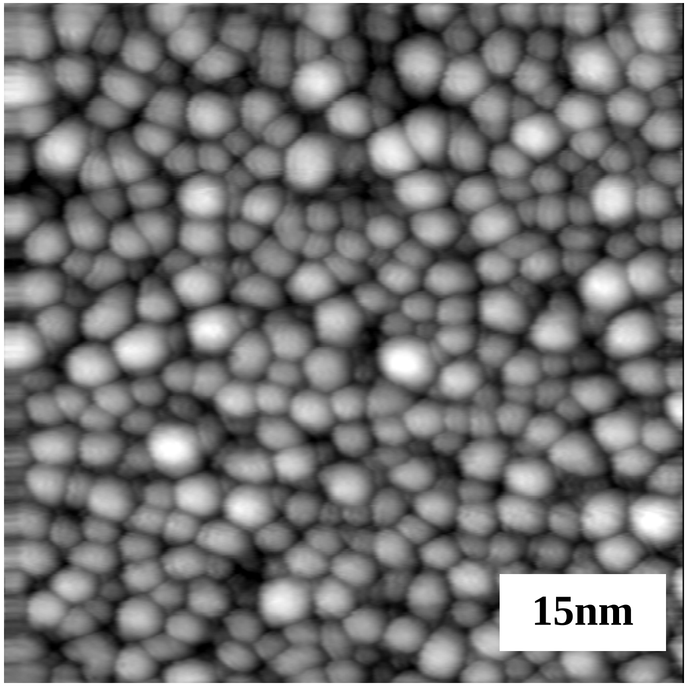
Ge is vapor despositioned by 2.5 atomic layers at 500 ℃.



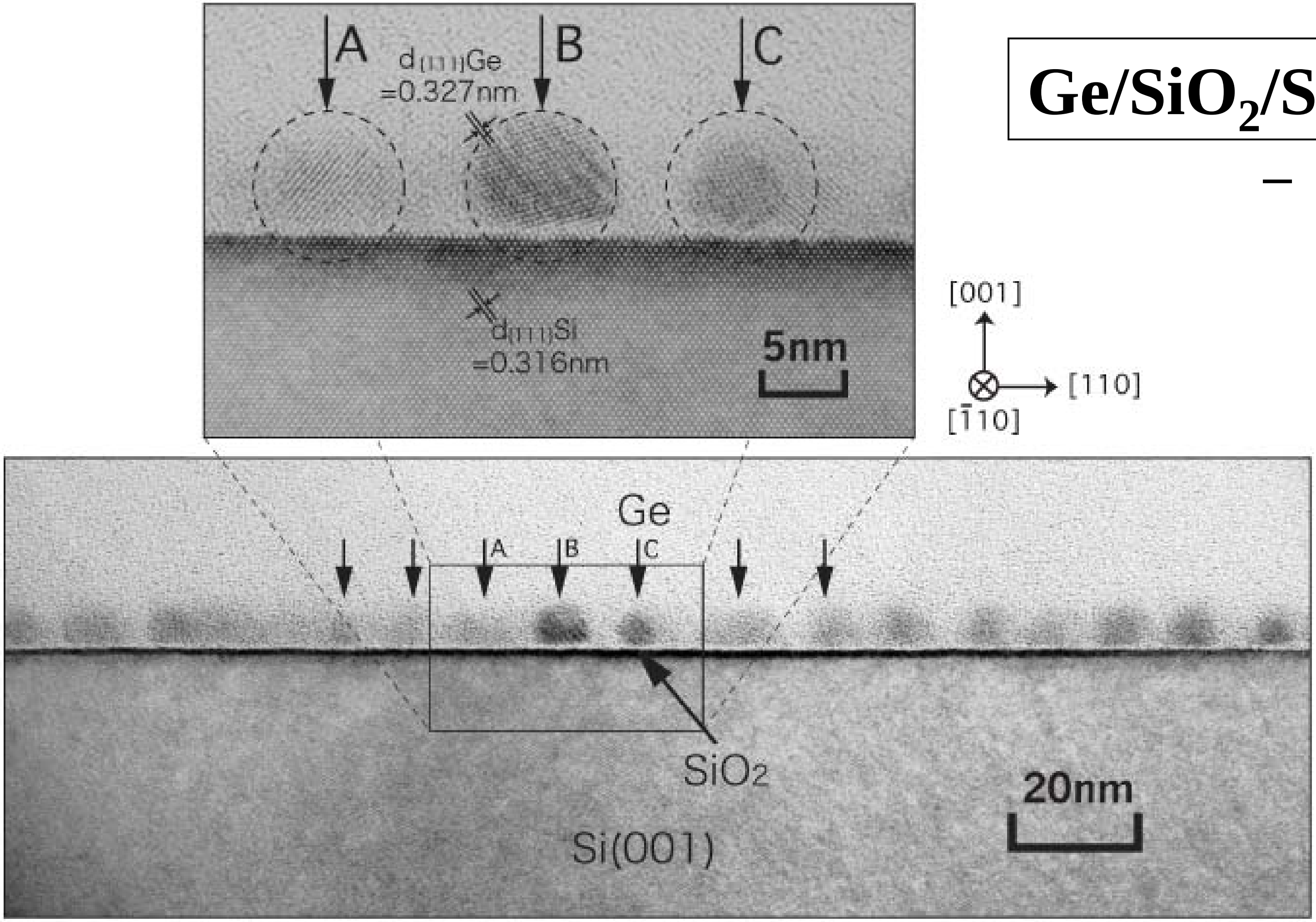
Size：～5nm

Surface density：$10^{12}cm^{-2}$ <

Si is vapor despositioned by 4 atomic layers at 500 ℃.



Transmission Electron Microscope Images of Ge Quantum Dots

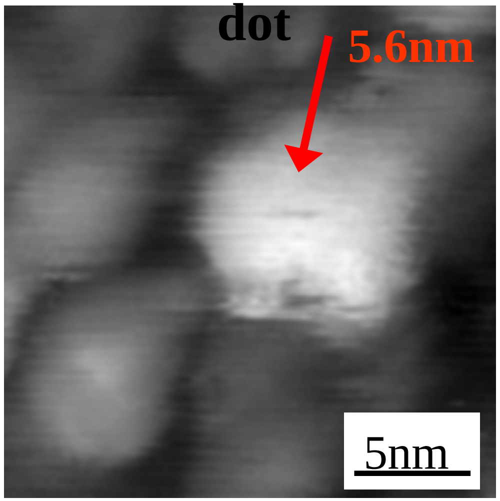


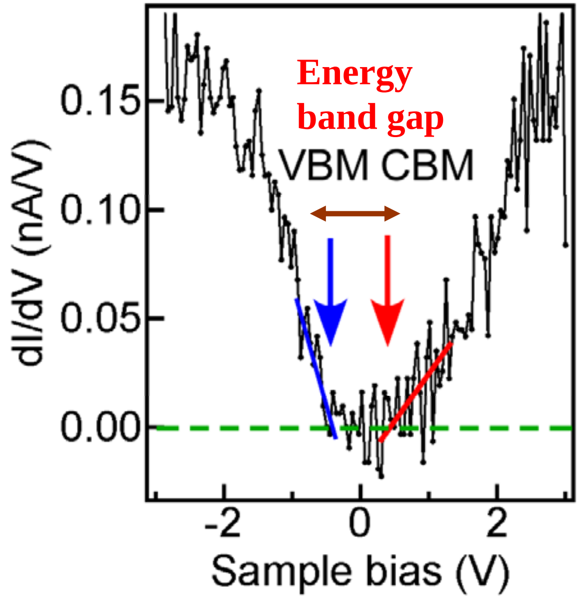
$Ge/SiO_2/Si(001)$

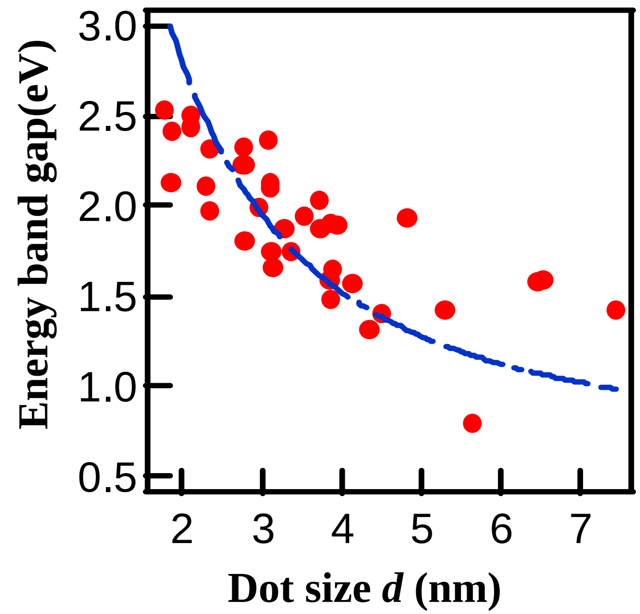
–

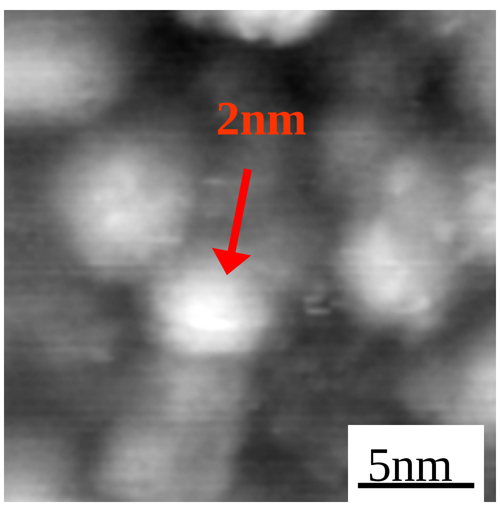
Ge Energy Band Gap Increase by Quantum Size Effect

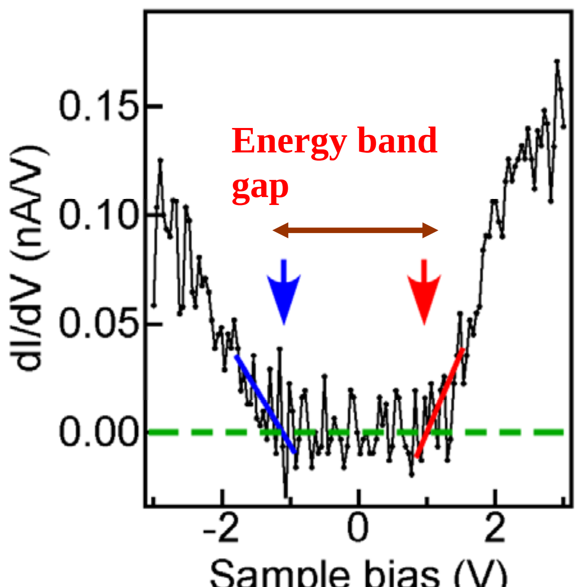
Ge quantum dot









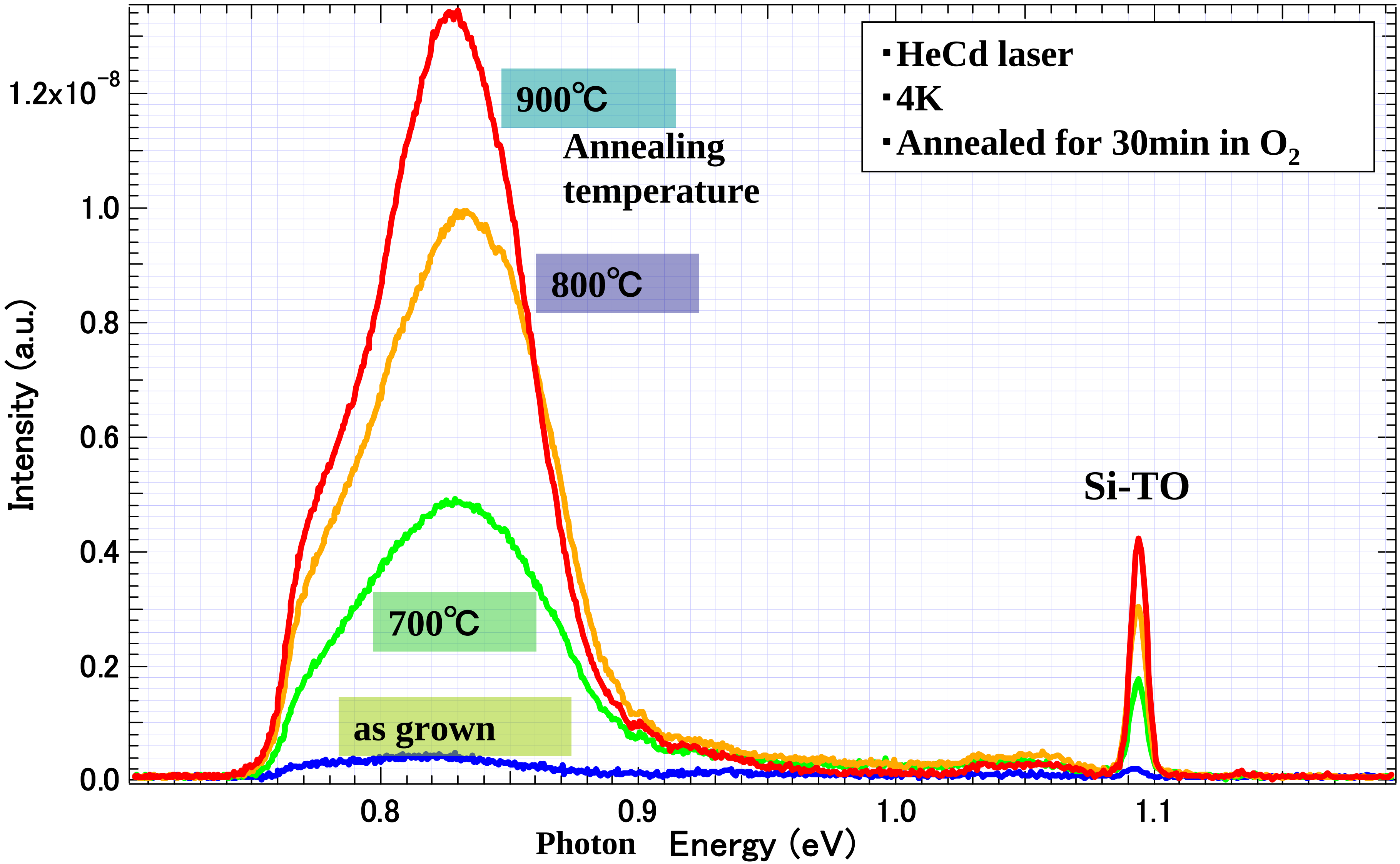


$$E \approx E_g + \frac{h^2}{2\mu d^2}$$

E_g : band gap in bulk
d **: dot size**
m **: reduced mass of carrier**
h **: Planck constant**

Detection of Strong Light Emission From the Ge Quantum Dot Sample

The wavelength range for optical communication (～1.5 mm) → Development to the Si photonics.



Summary of Lecture Two: Production and Application

Device (principle, physical properties, process, and applications)

Phenomenon:

Flow：laminar flow and turbulent flow.

Diffusion:vapor phase, liquid phase, and solid phase.

Heat transfer：conduction（thermal conductivity × temperature gradient）

Comparison: diffusion (diffusion coefficient × concentration gradient）

Radiation and convection current

Chemical reaction and self-organization

Pull toward good fortune: (transistor and nanocarbon)

In the next lecture: (Soft matter and self-organization)