Semiconductor Device Processing
(반도체 소자 공정 및 실습)

Lecture 2. Overview

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‘Real’ Schedule

Weekly Course Schedule		
Calendar	Description	*Remarks
1st week	Introduction/Semiconductor Process Overview	Lectures
2nd week	Semiconductor Process Overview	Lectures
3rd week	Growth of compound semiconductors – MBE & MOCVD	Presentations
4th week	Photolithography / Nanolithography	Presentations
5th week	PECVD / Oxidation	Presentations
6th week	Dry etching / Cleaning & Wet etching	Presentations
7th week	Diffusion / Ion implantation	Presentations
8th week	Mid-term Week	No midterm
9th week	Metallization (Ohmic Contacts) / TLM measurement	Presentations
10th week	Fabrication & Measurement of TLM patterns	Experiments
11th week		Experiments
12th week		Experiments
13th week		Experiments
14th week		Experiments
15th week		Experiments
16th week	Final Exam & Final Report	

Detailed Schedule

MARCH 2017

SUN	MON	TUE	WED	THU	FRI	SAT
			1	Lect. 2	3	4
5	6	Lect. 7	8	Lect. 9	10	11
12	13	Lect. 14	15	P1 16	17	18
19	20 (Mil. Service)	X 21 (Mil. Service)	22	P2 23	24	25
26	27	P3 28	29	P4 30	31	

2017 APRIL

SUN	MON	TUE	WED	THU	FRI	SAT
						1
2	3	4 P5	5	6 P6	7	8
9	10	11 P7	12	13 P8	14	15
16	17	18 X	19	20 X	21	22
23	24	25 P9	26	27 P10	28	29
30						

2017 MAY

SUN	MON	TUE	WED	THU	FRI	SAT
	1	2 P11	3	4 P12	5	6
7	8	9 Experiments	10 Experiments	11 Experiments	12	13
14	15	16 Experiments	17 Experiments	18 Experiments	19	20
21	22	23 Experiments	24 Experiments	25 Experiments	26	27
28	29	30 Experiments	31 Experiments			

2017 JUNE

SUN	MON	TUE	WED	THU	FRI	SAT
				1	2	3
4	5	6 Experiments	7 Experiments	8 Experiments	9	10
11	12	13 Final Exam.	14 Final Exam.	15 Final Exam.	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	

Assessment and grading

Attendance (5%)

Presentations and pre-reports (30%)

→ 15 min presentation

→ Pre-report for 6 presentation topics (select one topic per week, ~3 pages)

Final report (30%)

Final Exam (35%)

Presentation Subjects

1

1. **Molecular Beam Epitaxy (MBE)** 송한성, 차수형
2. **Metal-Organic Chemical Vapor Deposition (MOCVD))** 이길주, 김현명

2

3. **Photolithography** 김현영, 노혜빈
4. **Nanolithography** 유영진, 김무겸, 임지석

3

5. **PECVD** 박정환, 문승현
6. **Oxidation** 김경필, 이제성

4

7. **Dry etching** 이혜지, 최병휘
8. **Cleaning / Wet etching** 황진하, 김기영

5

9. **Diffusion** 민경민, 이선규
10. **Ion implantation** 이종헌, 석병탁

6

11. **Metallization** 김상민, 정준호
12. **Transmission Line Measurement (TLM)** 장건태, 장재형

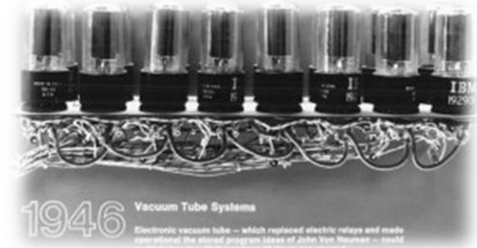
Contents

The semiconductor revolution

1940s

1st electronic general-purpose computer "Eniac"

- **Eniac** contains 17,468 vacuum tubes, weighed more than 30 tons, consumed 150 kW of electricity
- It could multiply two ten-digit numbers 40 times per second



Vacuum tubes

The fundamental building block of modern electronic device, "Transistor"

1947

1950s

- November 17, 1947 to December 23, 1947, John Bardeen and Walter Brattain at AT&T's Bell Labs in the US performed experiments. And solid-state group leader William Shockley saw the potential in this → **Transistor**
- Small size, low electric consumption, and **10 times faster than Eniac**

The semiconductor revolution

The Nobel Prize in Physics 1956

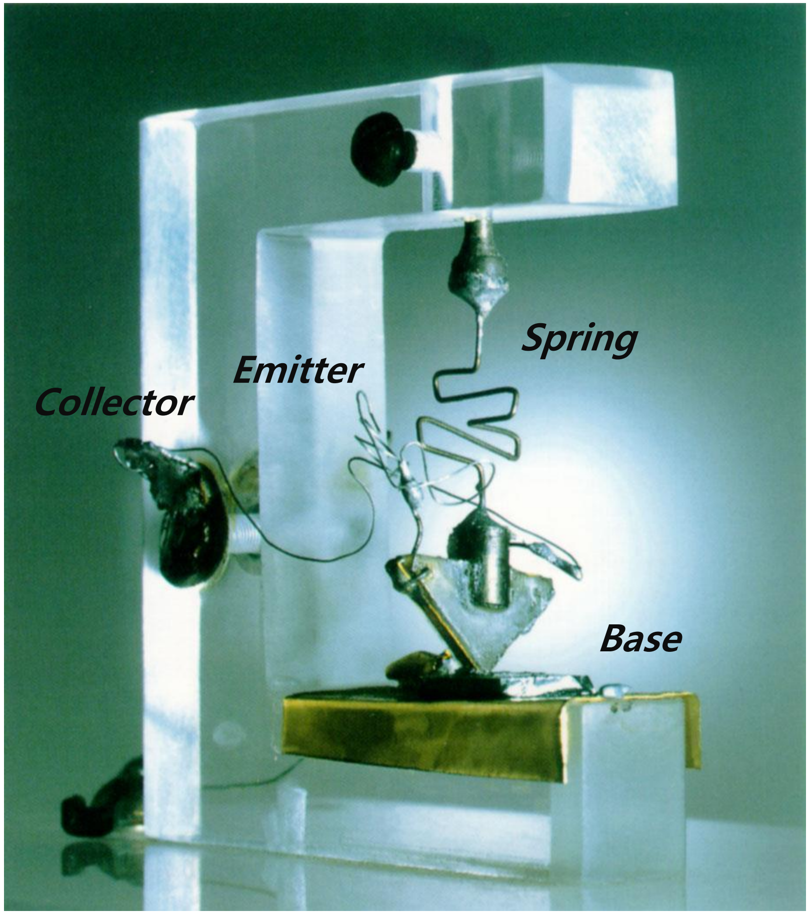
“for their researches on semiconductors and their discovery of the transtitor effect"

William Bradford
Shockley
1910–1989

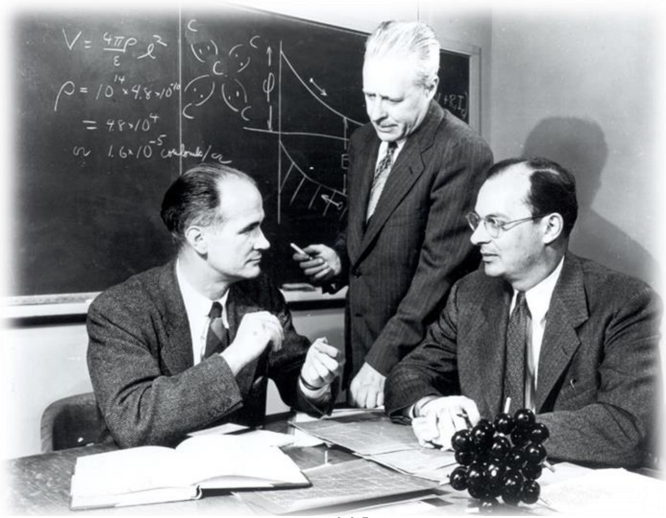
John
Bardeen
1908–1991

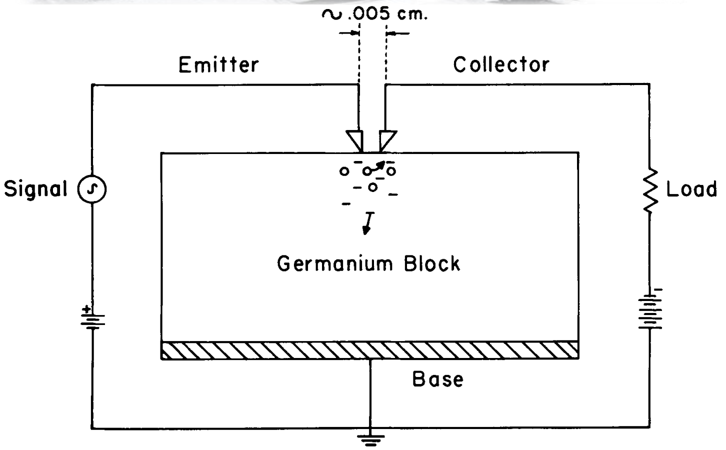
Walter Houser
Brattain
1902–1987

The semiconductor revolution



Bell telephone lab. Dec. 23, 1947

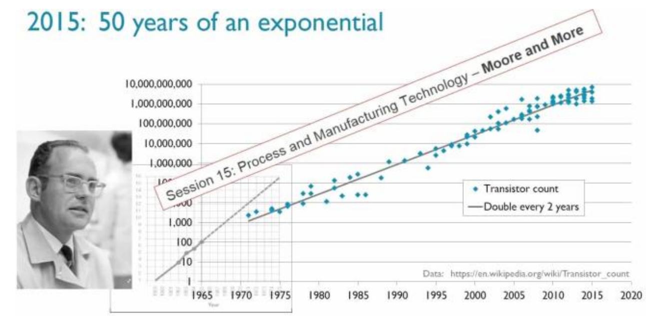


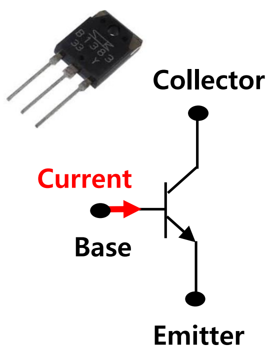


- Schematic plot of the first "point-contact" transistor

The semiconductor revolution

- <u>Transfer resister → **Transistor**</u>
- A small current at the base terminal can control or switch a much larger current between the collector and emitter terminals.





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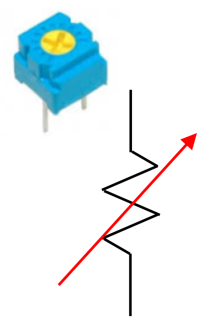
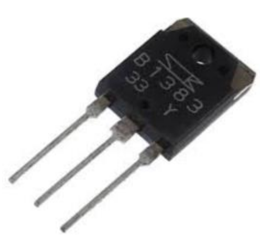


The Process Unit chip (PU chip) measures 678 mm^2 and consists of **3.99 billion transistors**, IBM, 2015.

- Transistor output is **5,700 times** larger than the wheat production by year

Transistor output in year : 10,000,000,000,000,000,000
= **2,700,000,000,000,000** / day

Wheat production by year: 703,000,000 t
= **480,000,000,000** / day

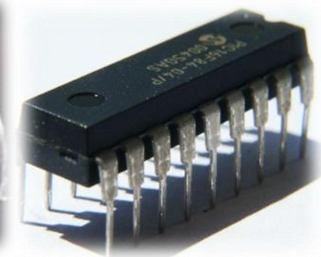


The semiconductor revolution

1959

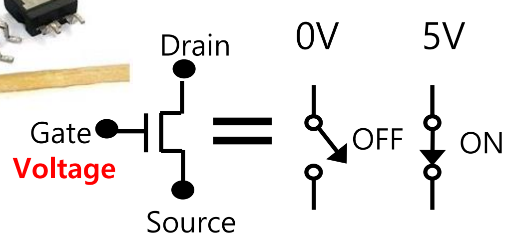
1960s

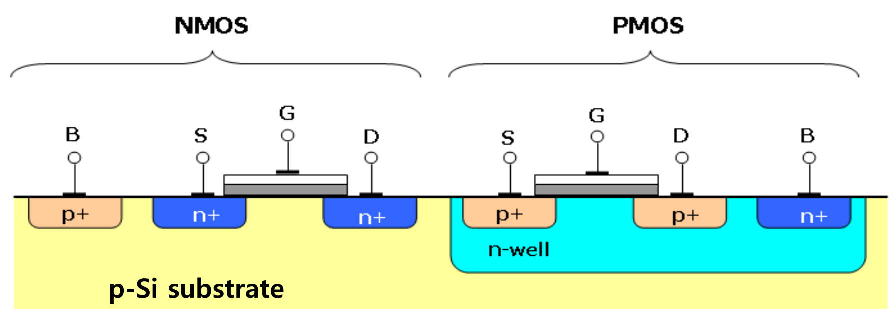
Development of semiconductor industry “MOSFET”



- In 1959, Dawon Jahng and Martin M. Atalla at Bell Labs invented the MOSFET
- **Integration** of **transistors** at silicon substrate → **circuit dimensions are reduced**

- **Role of turned-off switch** by Gate **voltage**



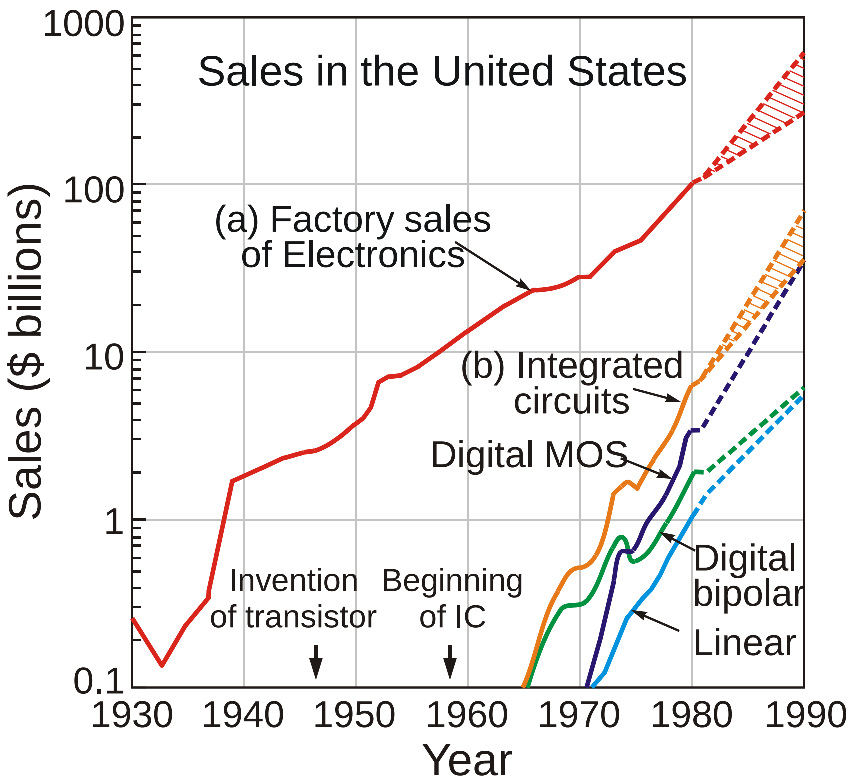


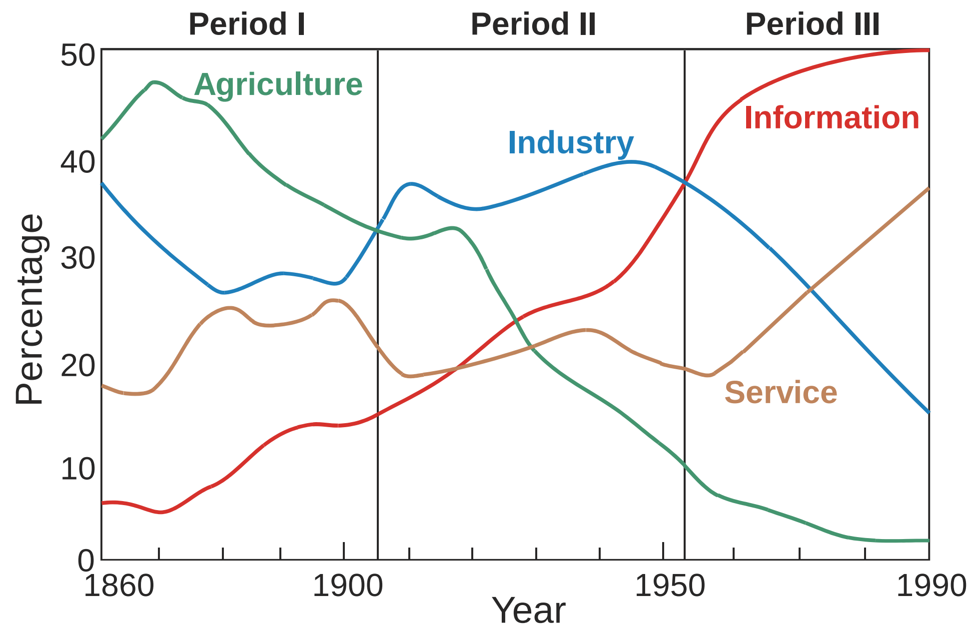
NMOS + PMOS (Complimentary MOSFET)
→ Method for large scale integration in the circuit

The semiconductor revolution

S. M. Sze, *J. Appl. Phys.* Vol. **22**, 1983

Factory sales of Electronics and IC



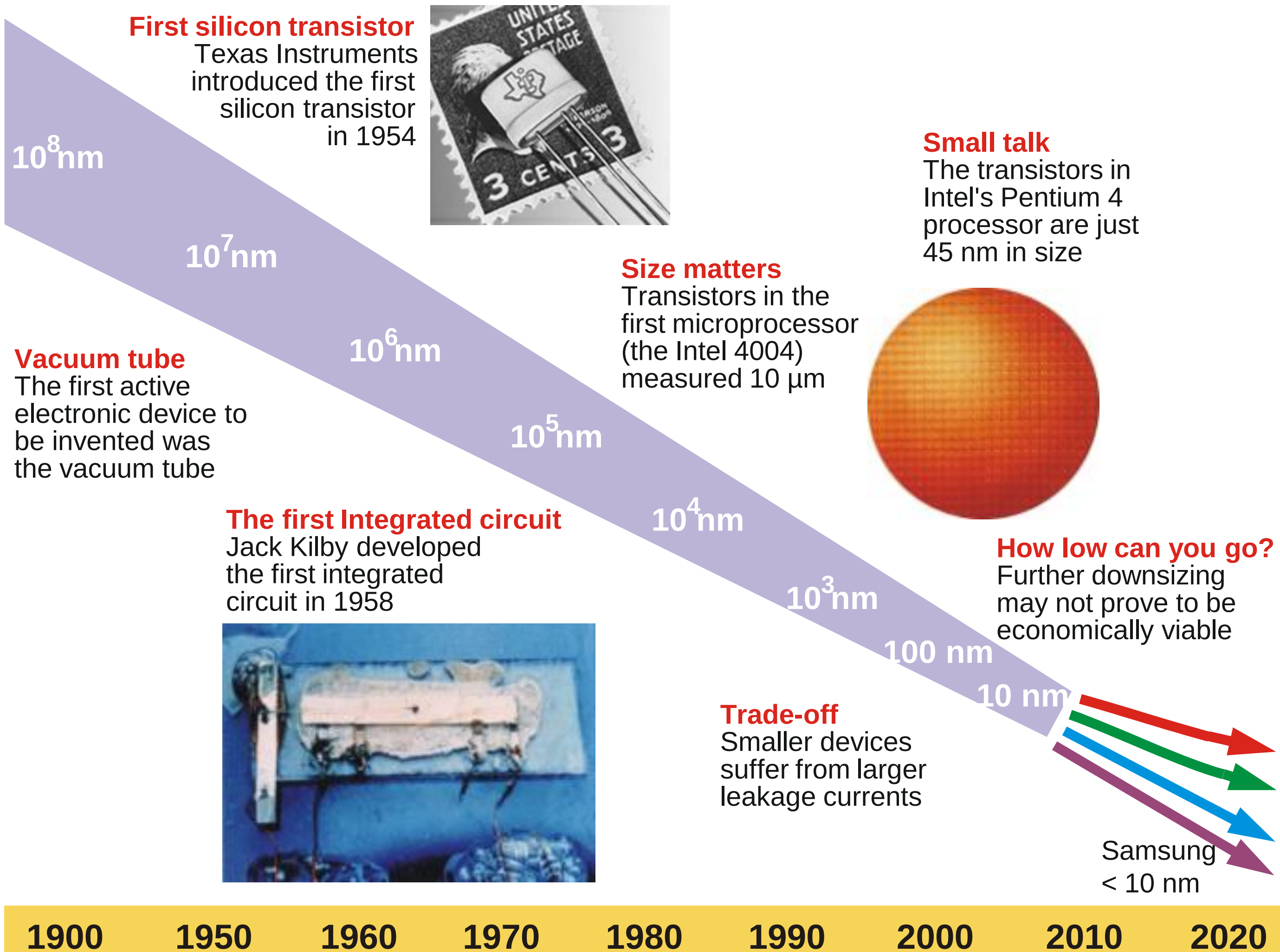


- **Factory sales of Electronics in the United States over the past 50 years and projected to 1990**
- **Integrated circuit market in the United States**

The semiconductor revolution

H. Iwai, H. wang, *Phys. World* Vol. **18**, 09, 2005

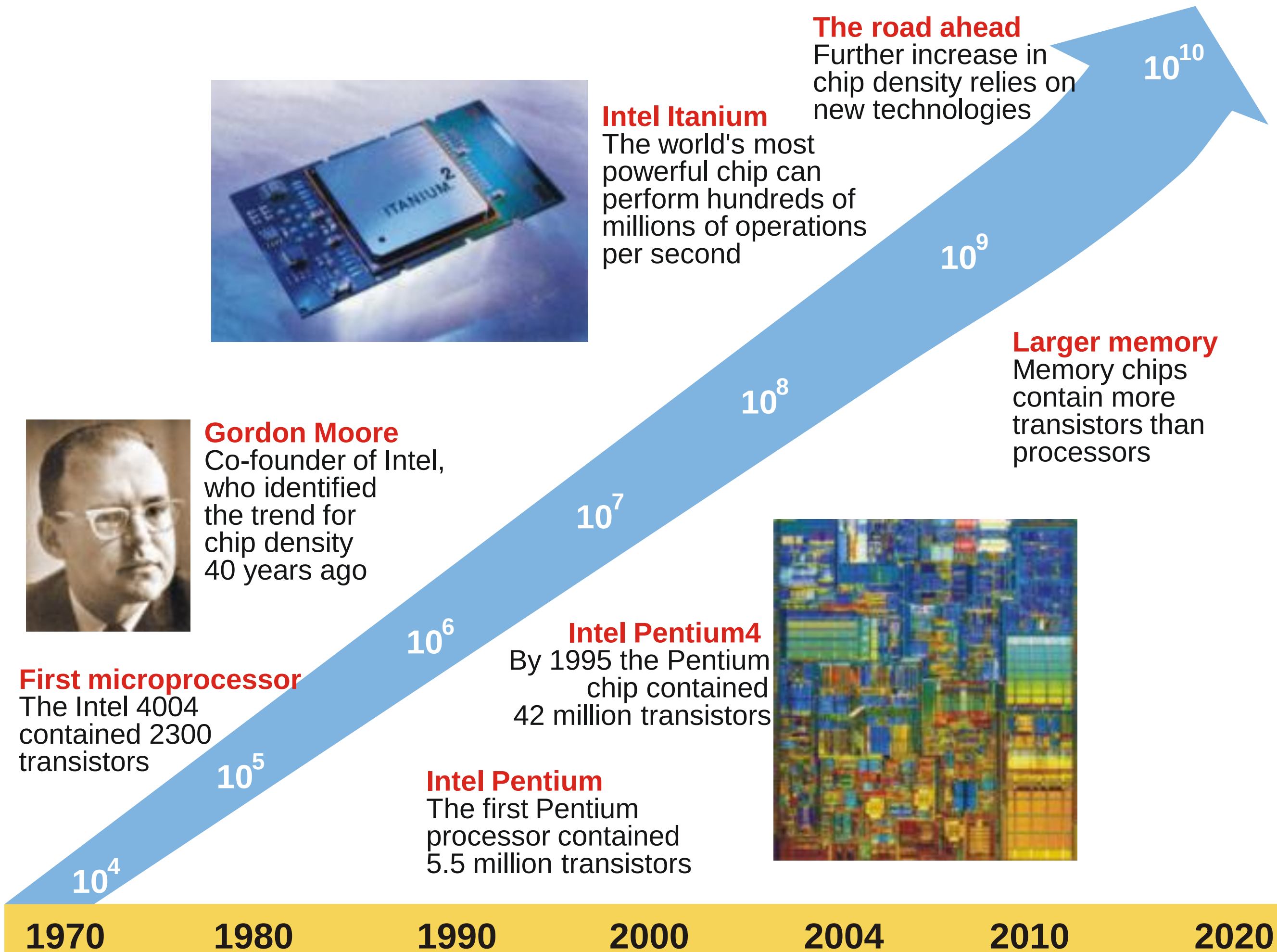
Moore's law I : device downsizing



The semiconductor revolution

H. Iwai, H. wang, *Phys. World* Vol. **18**, 09, 2005

Moore's law II : chip density



The semiconductor revolution

The Rise of Information and Communication Technology by "Light"

1963 — **Development of Compound semiconductor laser**

Alferov Kroemer
(The Nobel prize in physics, 2000)

1966 — **Invention of optical fiber**

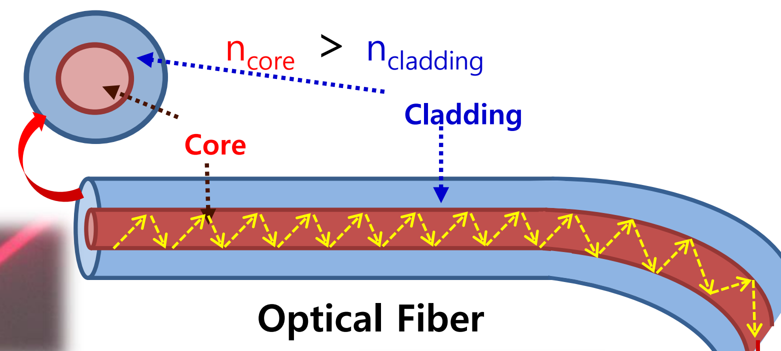
Charles Kun Kao
(The Nobel prize in physics, 2009)

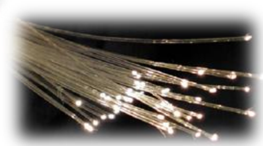
1976 — Development of 1.3 μm laser, fiber loss **(1dB/km)**

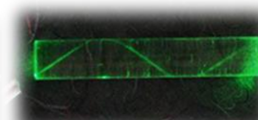
1979 — **Development of 1.55 μm laser, fiber loss (0.2dB/km)**

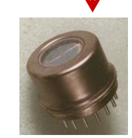
1980 — **Commercilization of optical communication**

2010s — **Commercilization of optical internet**









- An **optical fiber** is a cylindrical dielectric waveguide that transmits light along its axis, by the process of **total internal reflection**.

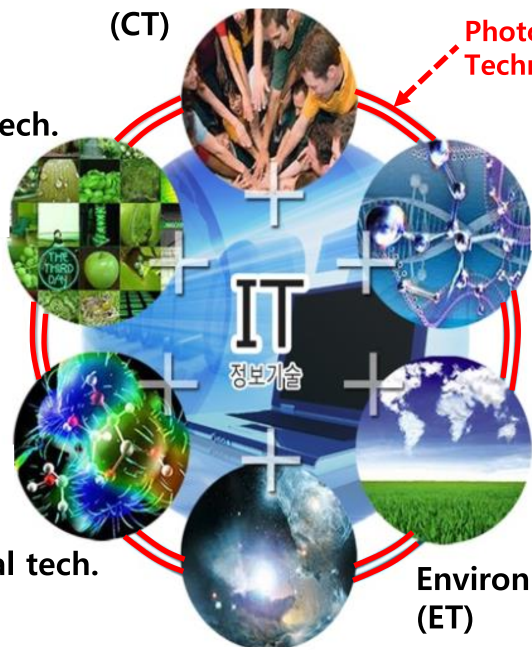
The semiconductor revolution

"IT & PT convergence"

IT: Information Technology
PT: Photonic Technology

2020s

Technology conversion



Cultural tech. (CT)
Photonic Technology
Green tech. (GT)
Nanotechnology (NT)
Biological tech. (BT)
Environmental tech. (ET)
Space tech. (ST)

Industry conversion

Manufacturing/Service

Info-communication

+ IT+PT

Before heterostructure : quantum electronics

The Nobel Prize in Physics 1964

"for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle"

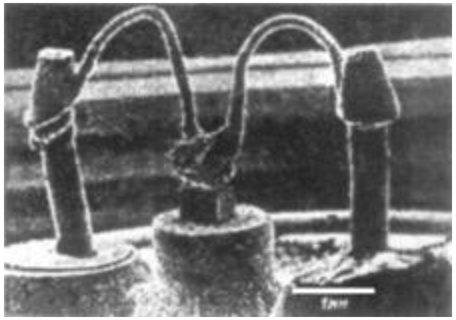
Charles Hard **Townes**
b. 1915

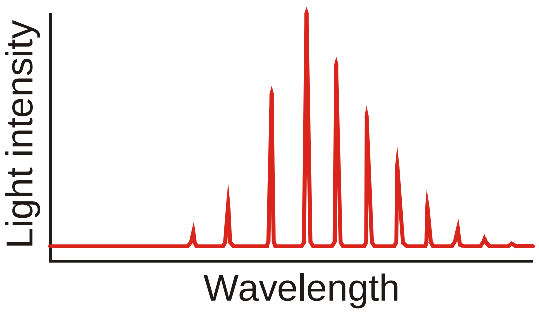
Nicolay **Basov**
1922-2001

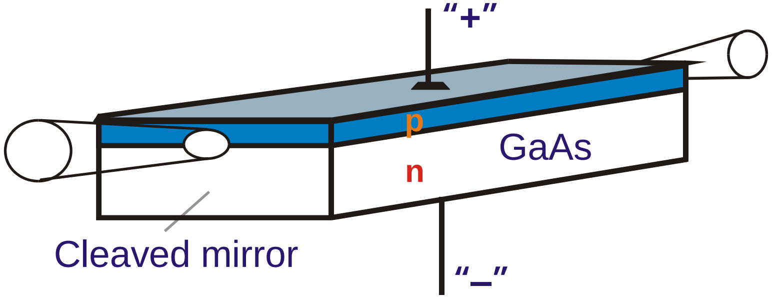
Aleksandr **Prokhorov**
1916–2002

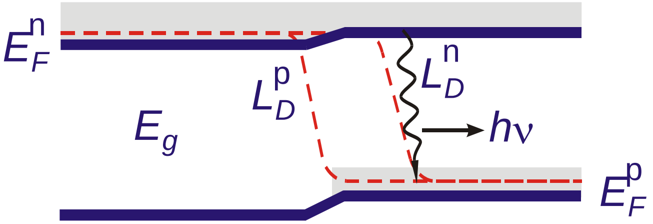
Before heterostructure : quantum electronics

- **January 1962:** observations of **superlumenscences** in GaAs p-n junctions (Ioffe Institute, USSR).
- **Sept.-Dec. 1962:** **laser action** in GaAs and GaAsP p-n junctions (General Electric , IBM (USA); Lebedev Institute (USSR).









Condition of optical gain: $E^n_F - E^p_F > E_g$

The impact of heterostructures

Z. Alferov, "Semiconductor Revolution in the 20th Century

1. **Heterostructure – a new kind of semiconductor materials:**

- Expensive, complicated chemically & technologically but most efficient

2. **Modern optoelectronics is based on heterostructure applications**:

- **Double heterostructure (DHS) laser –** key device of the modern optoelectronics
- **Heterostructure (HS) PD –** the most efficient & high speed photo diode
- **Optoelectronics integrated circuit (OEIC) –** only solve problem of high information density of optical communication system

3. **Future high speed microelectronics will mostly use heterostructures**

4. **High temperature, high speed power electronics**

- a new broad field of heterostructure applications

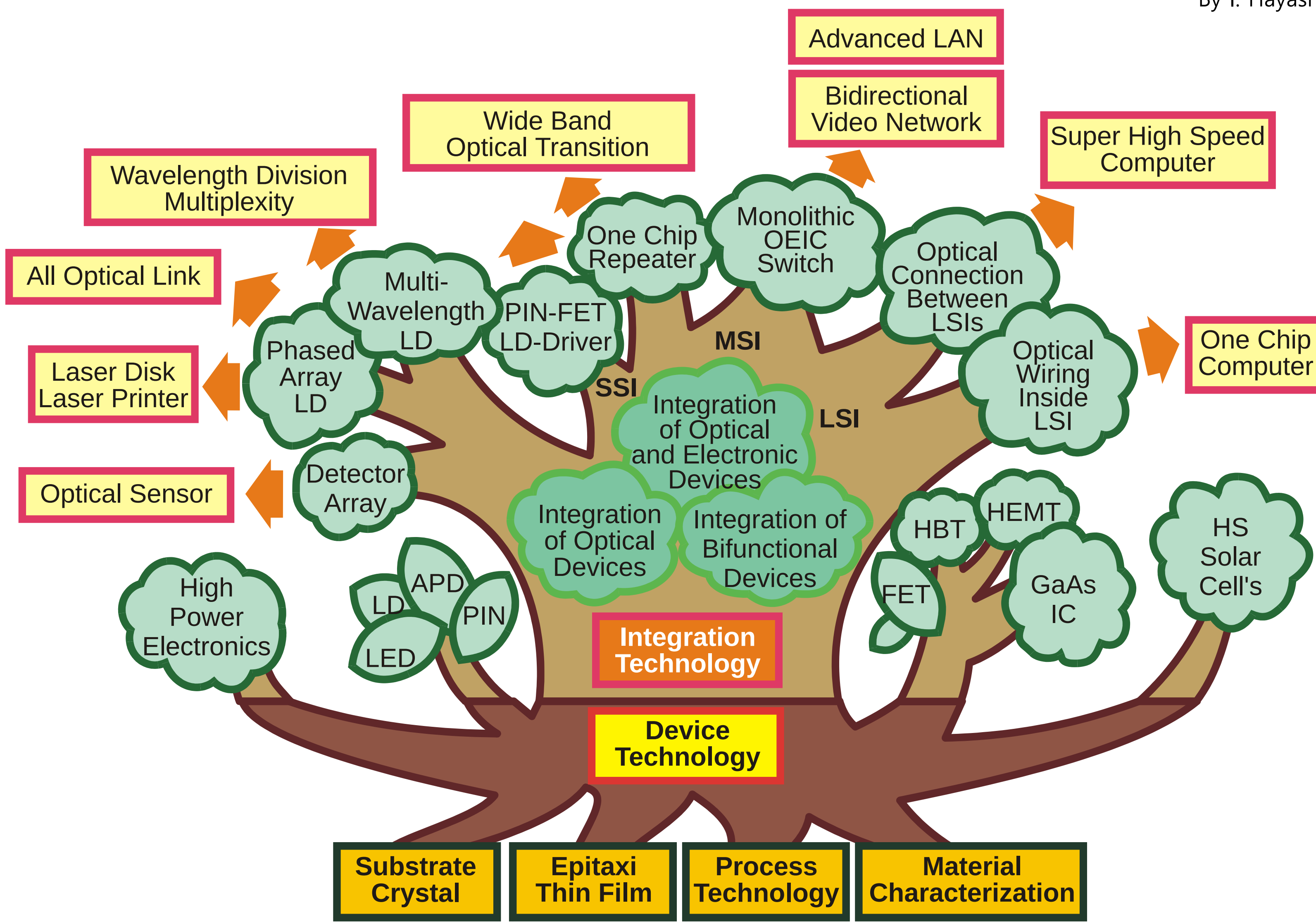
5. **Heterostructures in solar energy conversion:**

- The most expensive photocells and the cheapest solar electricity producer

6. **In the 21st century heterostrucures in electronics will reserve only 1% for homojunctions**

Heterostructures Tree

By I. Hayashi, 1985

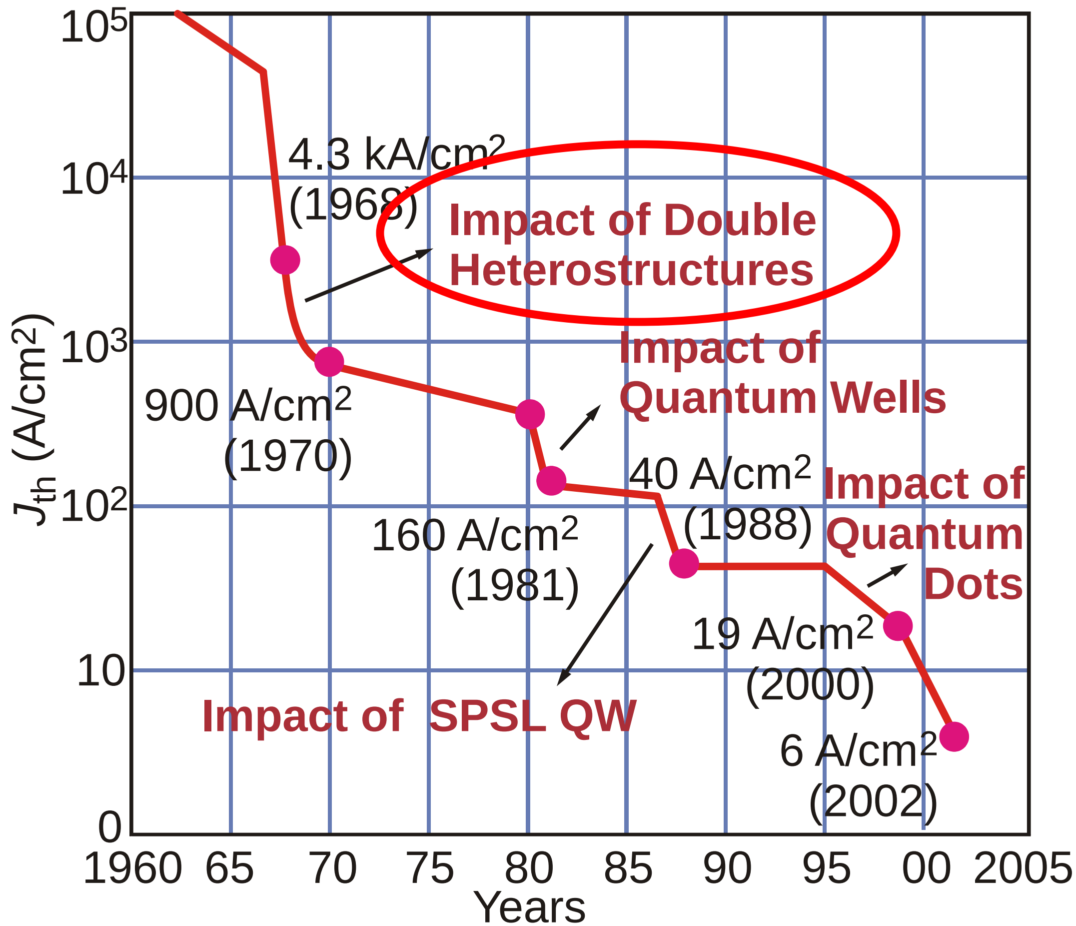


Heterostructures : hisrory and progress

Year	Progress	Contributor
1963	Conception of double heterostructure lasers : double injection, confinement	Alferov, Kazarinov, Kroemer
1966 1967	**GaAsP**-lattice mismatched DH LDs, 77k **AlGaAs**-lattice matched heterostructures	Alferov et al. Rupprecht et al.
1969	**AlGaAs**-DH LD: J_{thr}=4300 A/cm^2, RT, pulse, 770 nm, LED, transistor, solar cell elements	Alferov et al.
1970	**AlGaAs** LDs, CW, RT, J_{thr}=940 A/cm^2 **InGaAsP** : from IR to visible	Alferov et at., Hayashi, Panish, Alferov et al., Antipas et al.
1974	Quantum size effect in **GaAs/AlGaAs** (multi) graded structure	Dingle et al., Esaki, Chang, Tsu et al.
1975	First **AlGaAs/GaAs** MQW optically pumped laser, T=15k, hv=1.53 eV	Van der Ziel, Dingle et al.
1978	**AlGaAs/GaAs** LD, RT, **QUANTUM WELL (QW)** J_{thr}=3x10^3 A/cm^2, λ=800 – 840 nm	Dupius, Dapcus, Holonyak et al.
1980	QW heterostuctures: transistors, Quantum Hall effect	Mimura et al., Klitzing et al.
1982	**AlGaAs/GaAs** GRINSH, J_{thr}=160 A/cm^2	Tsang et al.
1983	**GaAs/InGaAs** strained LD, RT, CW	Holonyak et al.
1996 1997	**InGaAs/GaAs** QDs LDs, RT, CW J_{thr}=97 A/cm^2, P=160 mW, hv=1.3 eV	Bimberg, Park, Alferov et al.
2000	**InGaAs/GaAs** QD transverse&VCSEL, λ=1.3 μm, J<100 A/cm^2, P=2.7 W	Ustinov et al.
1994 2000	Quantum engineering Quantum cascade lasers: λ=4 – 11 μm, T=320k	Faist, Capasso, Sirtory, Cho
2000	**Nobel Prize → "For developing semiconductor Heterostructures used in high-speed- and opto-electronics"**	Zhores I. Alferov, Herbert Kroemer

Heterostructures : hisrory and progress

Milestones of semiconductor lasers



- Evolution and revolutionary changes
- Reduction of dimensionality results in improvements

Heterostructures : hisrory and progress

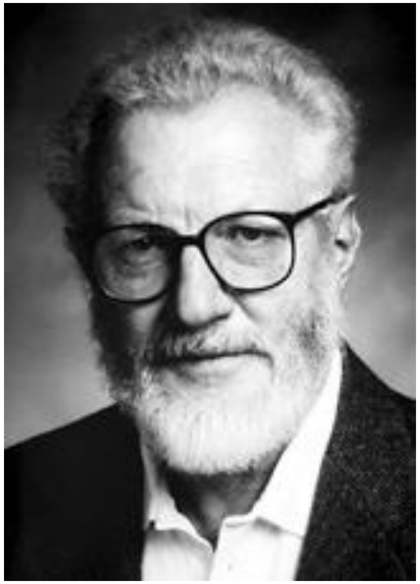
The Nobel Prize in Physics 2000

"for basic work on information and communication technology"

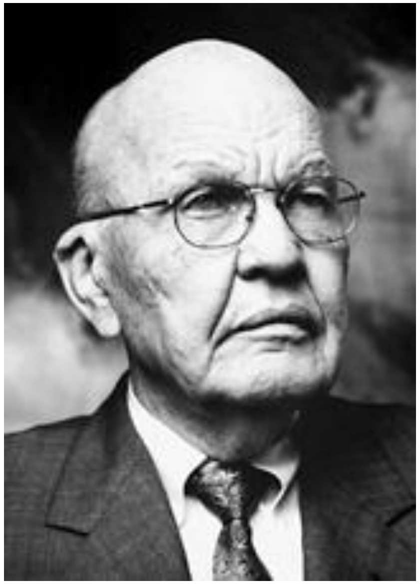
"for developing semiconductor heterostructures used in **high-speed- and opto-electronics**"

"for his part in the invention of the integrated circuit"

Zhores I. **Alferov**
b. 1930



Herbert **Kroemer**
b. 1928



Jack S. **Kilby**
1923–2005

Heterostructures : hisrory and progress

THE NOBEL PRIZE IN PHYSICS

Speech by Professor Tord Claeson of the Royal Swedish Academy of Sciences.

. . . IT is viewed as a prime mover in the economic upswing our society has experienced over the past decade.

This year's Nobel Prize in Physics rewards contributions to the early developments of microelectronics and photonics, focusing on the integrated circuit, or "chip," as well as semiconductor heterostructures for lasers and high-speed transistors. . . .

Semiconductor heterostructures can be regarded as laboratories of two-dimensional electron gases. The 1985 and 1998 Nobel Prizes in Physics for quantum Hall effects were based on such confined geometries. They can be reduced further to form one-dimensional quantum channels and zero-dimensional quantum dots for future studies. . . .

Some basic definitions of heterostructures

❖ **Heterostructures:**

- Crystal consisted of **one** or **more junctions** between **different semiconductors with different E_g**, lattice constats, layer thickness

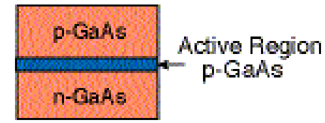
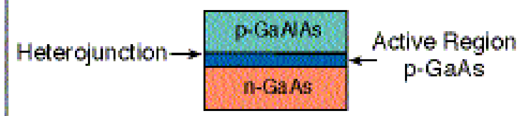
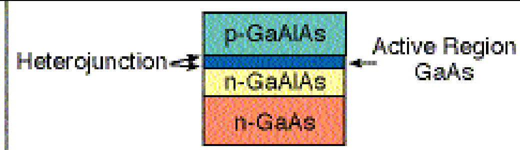
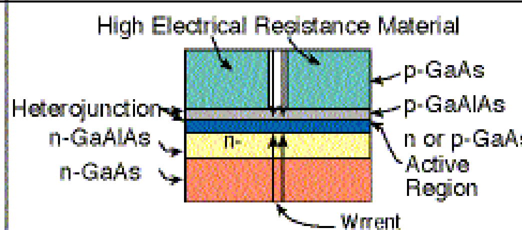
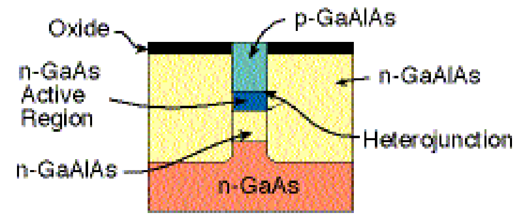
❖ **Design:**

- Subsrate + a sequence of thin layers

❖ **Potential well:**

- Active layer $E_g^a < E_g^c$ of claddings (barriers)
- $L_x^a << L_y, L_z$ and $L_x^a >> \lambda_B$ and a_B

(λ_B Is the de Broglie wavelength of the carriers, a_B is the Bohr exciton radius)

Laser Type	Laser Structure	Radiation Confinement
Homojunction		A little Confinement in paper plane
Single Heterojunction		Good Confinement in one side in perpendicular plane (paper)
Double Heterojunction		Good Confinement in both sides in perpendicular plane (paper)
Gain-Guided Stripe		
Buried Heterojunction (Index-Guided Stripe Geometry)		Good Radiation Confinement in both Horizontal and Perpendicular Planes

❖ **Quantum well:**

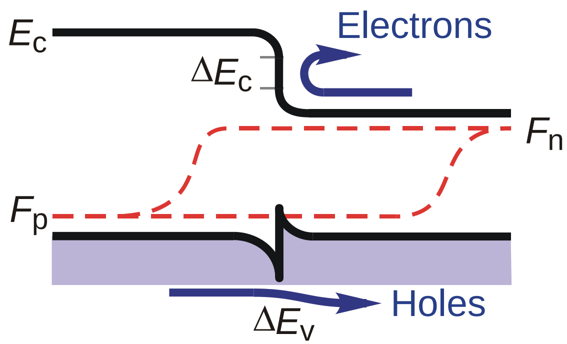
- $L_x^a << L_y, L_z$ and $L_x^a \sim \lambda_B$ and a_B
- The carrier movement in the x direction is **quantized.**
- The carrier energy becomes definte **discrete.**

→ Optical and carrier confinement due to ΔE_g and Δn_r

Classical heterostructures

Fundamental physical phenomena in classical heterostructures

(a)

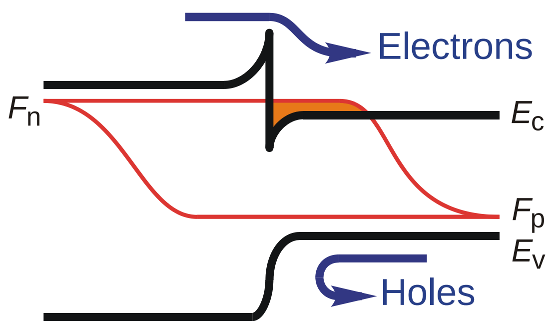


One-side Injection

Proposal — 1948 (W. Shokley)

Experiment — 1965 (Zh. Alferov *et al.*)

(b)

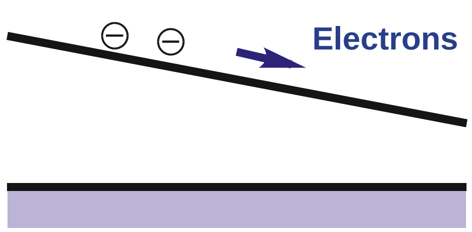


Superinjection

Theory — 1966 (Zh. Alferov *et al.*)

Experiment — 1968 (Zh. Alferov *et al.*)

(c)



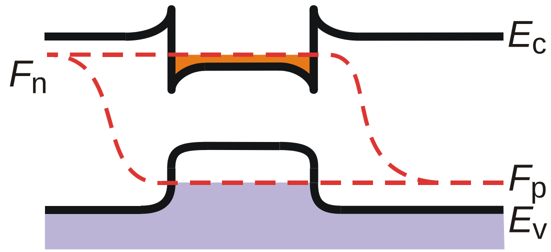
Diffusion in built-in quasielectric field

Theory — 1956 (H. Kroemer)

Experiment — 1967 (Zh. Alferov *et al.*)

Classical heterostructures

(d)

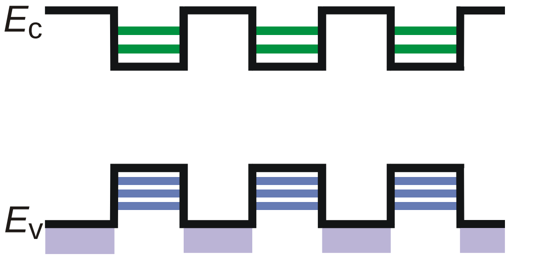


Electrical and optical confinement

Proposal — 1963 (Zh. Alferov *et al.*)

Experiment — 1968 (Zh. Alferov *et al.*)

(e)



Superlattices and quantum wells

Theory — 1962 (L.V. Keldysh)

First experiment — 1970 (L. Esaki *et al.*)

Resonant tunnelling — 1963 (L.V. Iogansen)

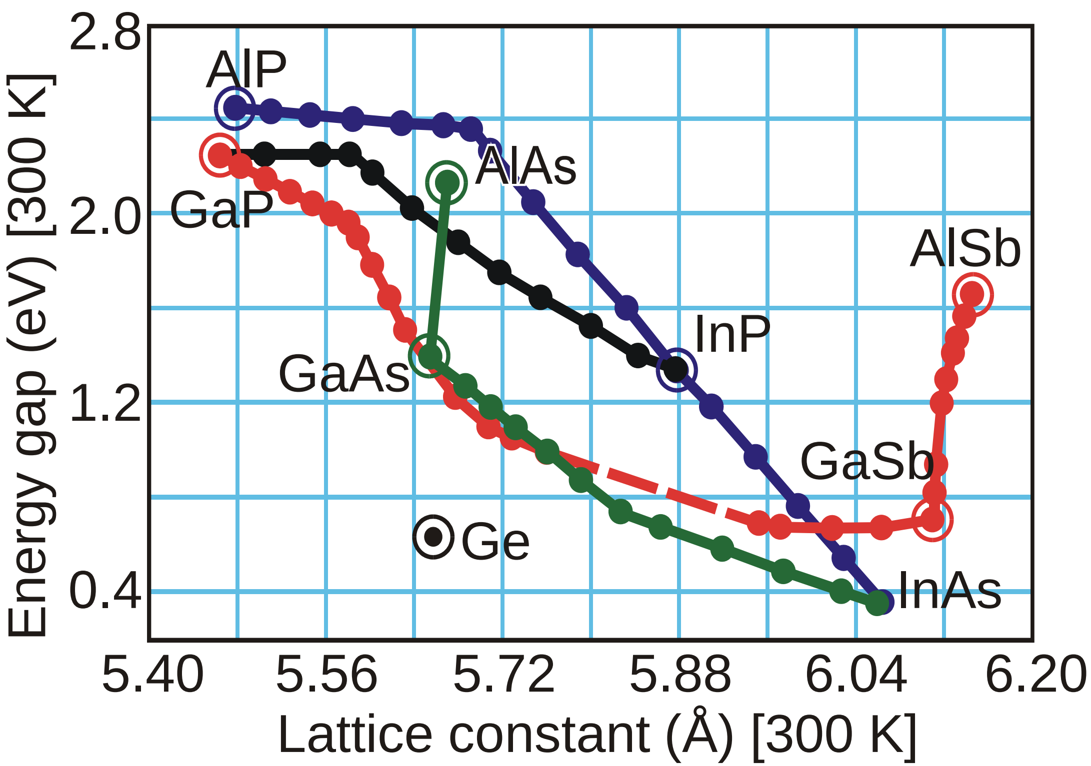
In Quantum Wells — 1974 (L. Esaki *et al.*)

- **Lattice-matched structures are necessary**
- **For lattice matching, multicomponent solid solution should be used**
- **In principle, epitaxial growth technology is necessary**

Heterostructures – a new kind of semiconductor materials

Long journey from infinite interface recombination to ideal heterojunction

Lattice matched heterostructures

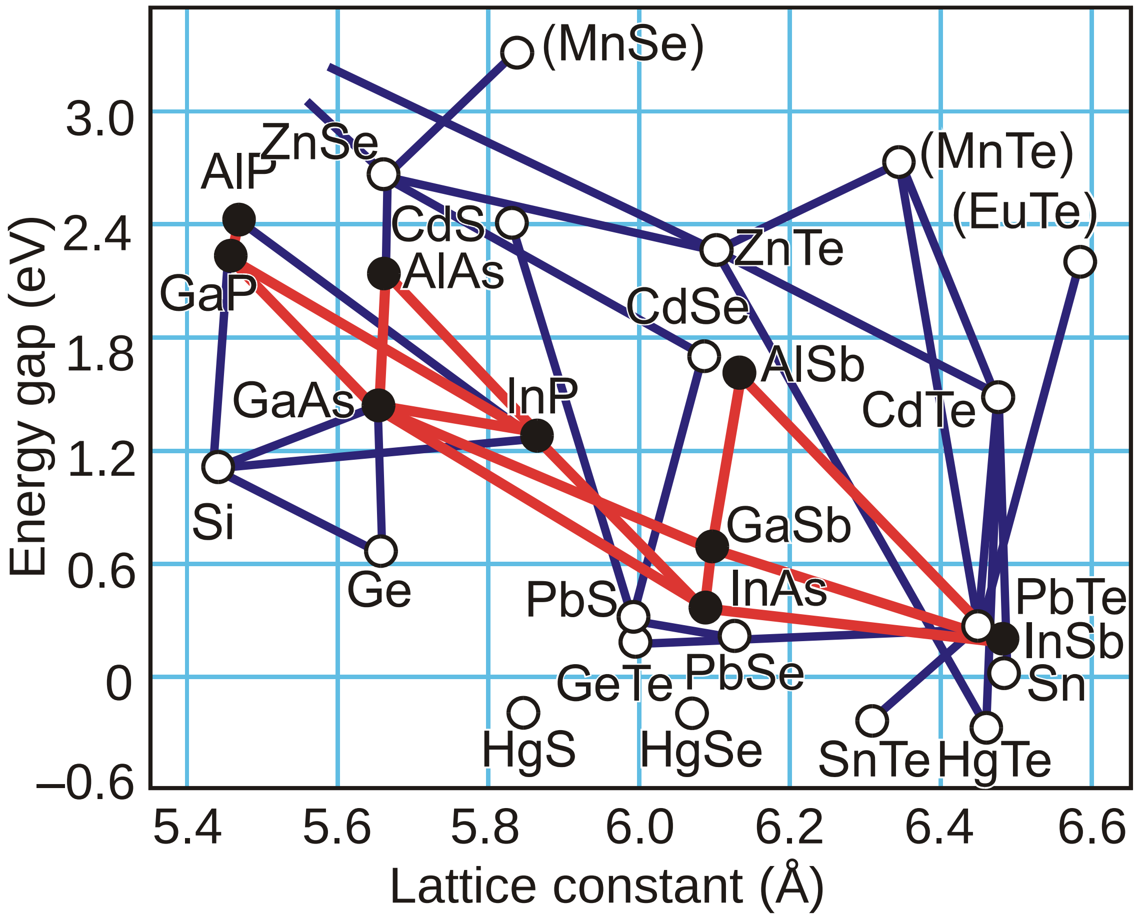


- **Ge–GaAs–1959**
  (R. L. Anderson)
- **AlGaAs–1967**
  (Zh. Alferov *et al.*,
  J. M. Woodall &
  H. S. Rupprecht)
- **Quaternary HS (InGaAsP & AlGaAsSb)**

  Proposal–1970
  (Zh. Alferov *et al.*)

  First experiment–1972
  (Antipas *et al.*)

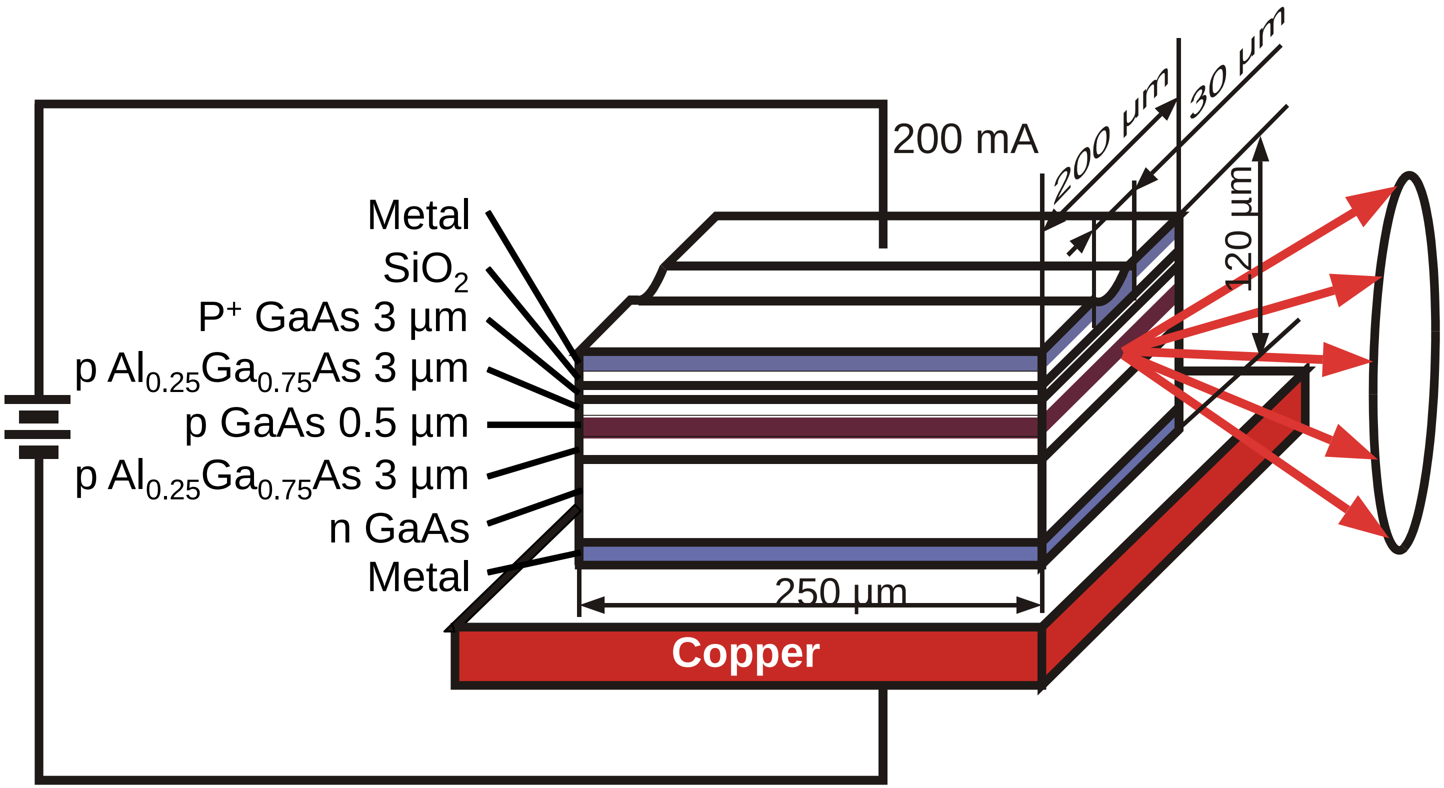
Heterostructures – a new kind of semiconductor materials



- **Energy gaps vs. lattice constants for semiconductor IV elements, III-V and II(V)-VI compounds and magnetic materials in parentheses.**
- **Lines connecting the semiconductors, red for III-V, and blue for others, indicate quantum heterostructures, that have been investigated.**

Heterostructures – DHS laser

Schematic representation of the DHS injection laser in the first CW-operation at room temper ature

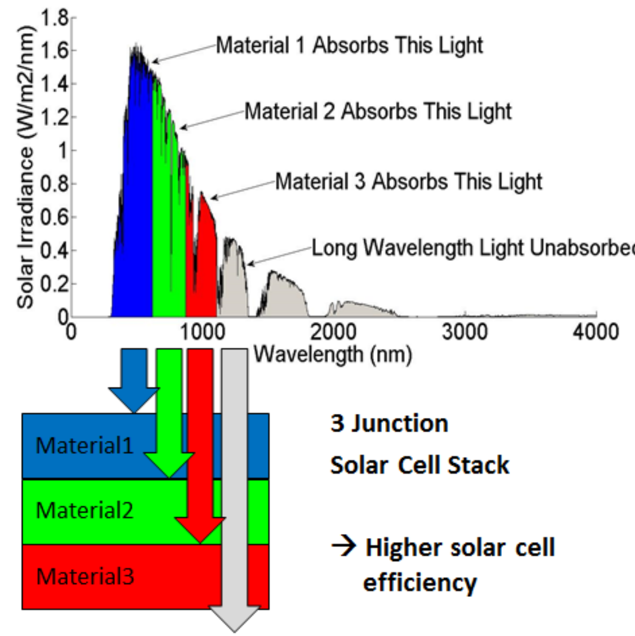


- **Fundamental need for structures with well-matched lattice parameters**
- **The use of multicomponent solid solutions to match the lattice parameters**
- **Fundamental need for epitaxial growth techniques**

Heterostructures – space solar cell

Heterostructure solar cells

- **Space station "Mir" equipped with heterostructure solar cells**



3 Junction Solar Cell Stack

→ Higher solar cell efficiency

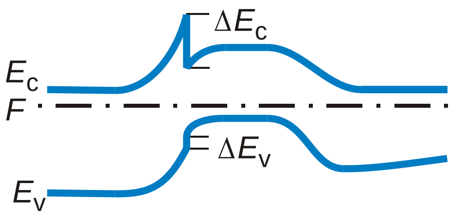
- **Multi-junction solar cell**
  Next-generation multijunction solar cells comprise multiple individual solar cells <u>grown on top of each other</u>

→ they can absorb a wider range of the sun spectrum

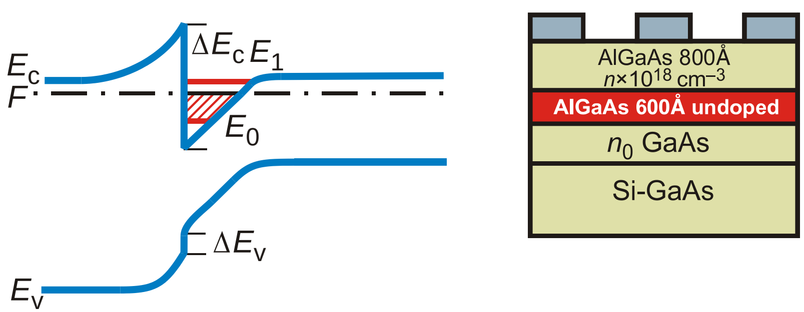
Heterostructures – microelectronics

Suggestion—1948 (W.Shockley)
Theory—1957 (H.Kroemer)
Experiment—1972 (Zh.Alferov *et al.*)
AlGaAs HBT

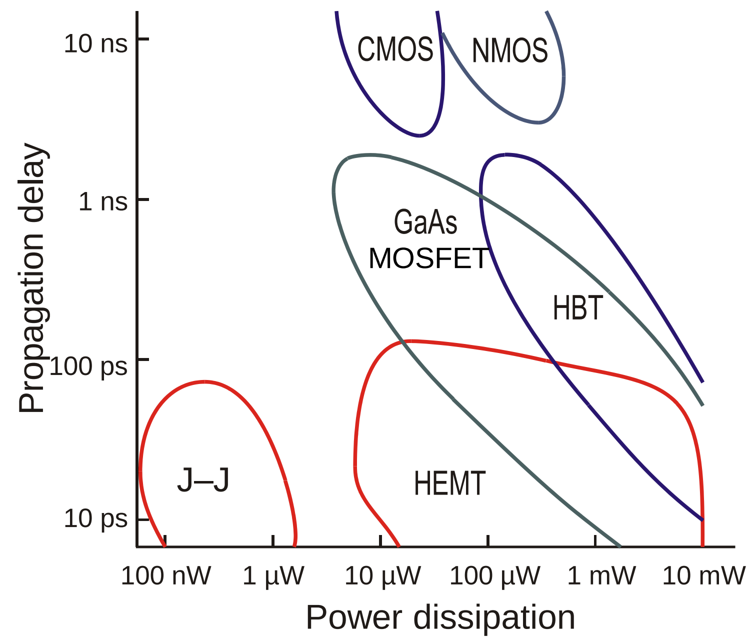
Heterojunction Bipolar Transistor



HEMT—1980 (T.Mimura et al.)



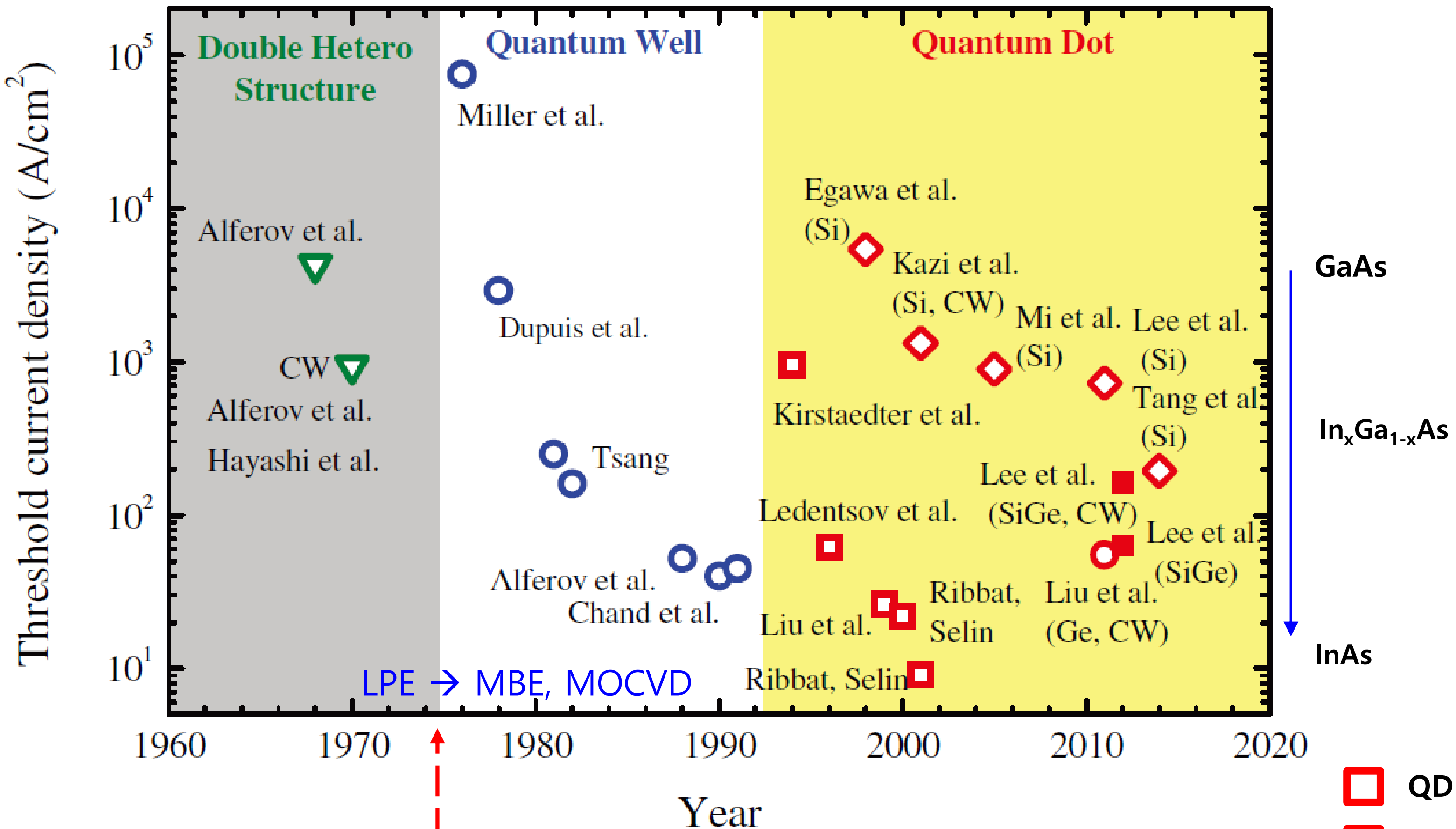
n AlGaAs-*n* GaAs Heterojunction

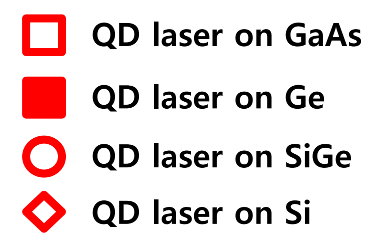


Speed-power performances

The evolution of laser diode performance

J. Phys. D: Appl. Phys. 48 (2015) 363001





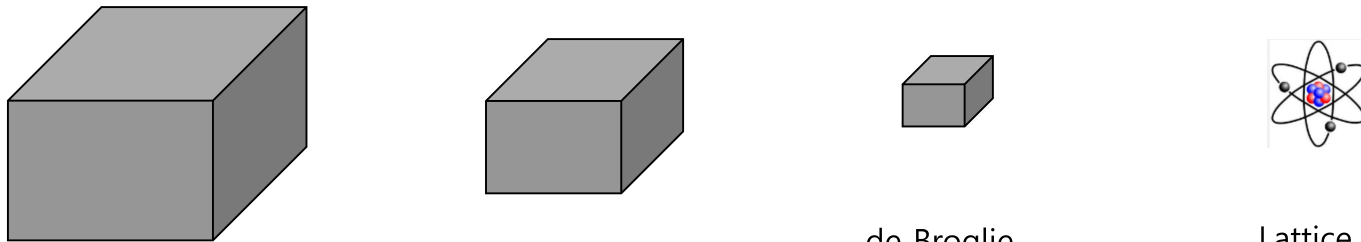
The development of new growth techniques

- **Molecular beam epitaxy (MBE)**
- **Metal organic chemical vapour deposition (MOCVD)**

→ Enabled the crystal deposition to be controlled on an atomic scale

Quantum confined structures

1 cm	1 μm	10 nm	1 Å



Macroscopic	Wavelength of light	de Broglie wavelength	Lattice constant
Volume semiconductor	**Waveguide**	**Quantum size**	**Atom**

de Broglie wavelength

$$E = h\nu$$

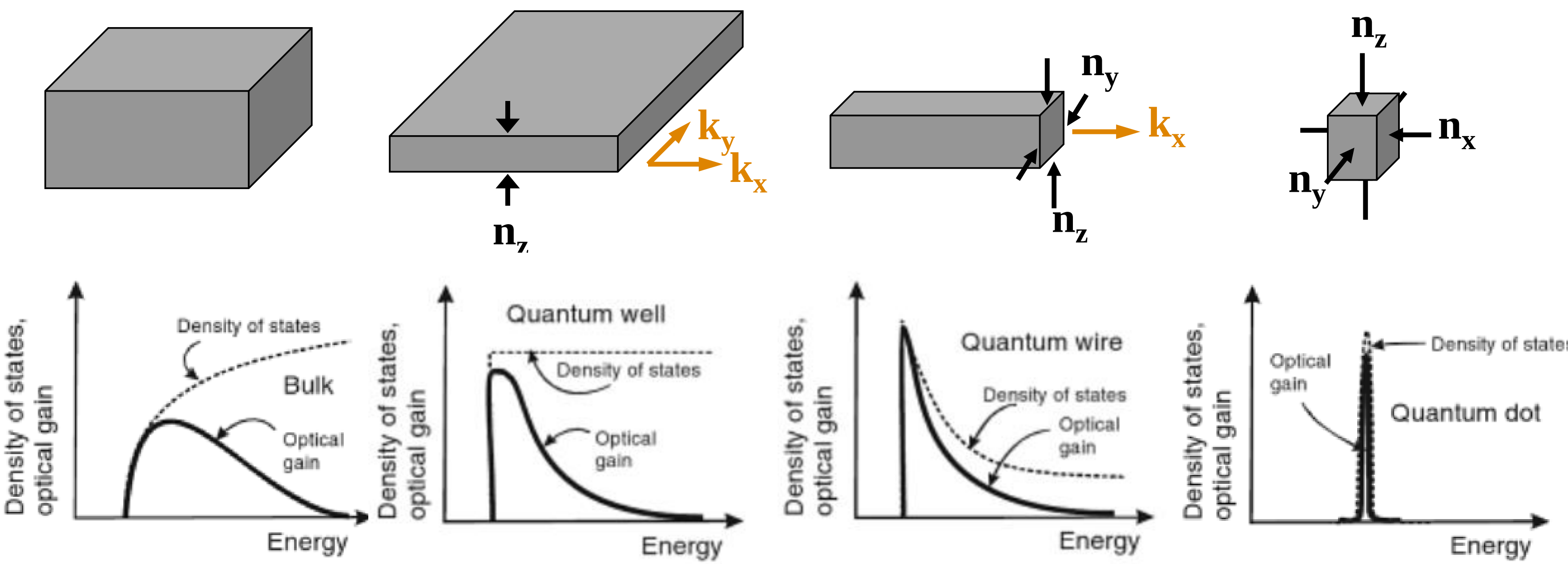
$$mv^2 = h\frac{v}{\lambda}$$

$$\lambda = \frac{h}{mv} = \frac{h}{p}$$

- ***Size quantization effects*** can be already pronounced at a thickness ten to a hundred times larger than the lattice constant.
- An electron in GaAs, **λ~24 nm**, this implies that we need structures of **thickness ~ 10 nm** in order to observe quantum-confinement effects.

Quantum confined structures

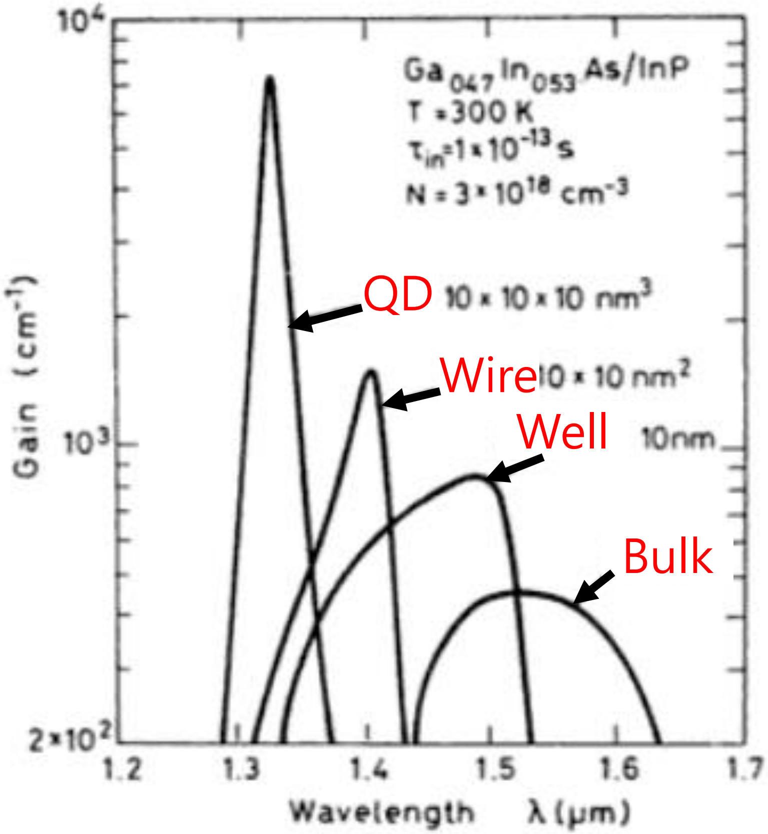
Bulk | **Quantum Wells** | **Quantum Wires** | **Quantum Dots**



Continuous Energy → **Discrete Energy**

Structure	Bulk	Quantum wells	Quantum wires	Quantum Dots
Quantum confinement	none	1D	2D	3D
Free dimensions	3D	2D	1D	0D

Quantum confined structures



Calculated material gain in $Ga_{0.47}In_{0.51}As/InP$ system

Same electron injection ($N = 3 \times 10^{18}$ cm^{-3})

The **peak gain increases** on going from bulk to QD.

However, **gain bandwidth decrease** from bulk to QD.

Questions or comments?