SINGAPORE UNIVERSITY OF TECHNOLOGY AND DESIGN

Term 7- Sept 2025

Nanoelectronics and Technology (01.119/99.503)

Shubhakar K
16-Sept- 2025

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Office location: 1.602-26

Outline

- Course information
- Course background
- Introduction to Nanotechnology and Nanoelectronics
- Latest news on Nanoelectronics and Semiconductor industries
- Review of semiconductors- Silicon

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Course information

- (01.119/99.503)-UG and PG course combined

  Class Venue

  - TT-1.408 (Building 1 Level 4)

- Timings:

  Tuesday 3.30PM – 6.00PM
  Thursday 3.30PM – 6.00PM

Course information

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Homework

Homework questions will be uploaded on edimension on Friday from Week 2

Submission: Next week Friday (5PM)

UG

Grading and assessment:

- Homework - 10%
- Mid-term Exam-25%
- Final Exam-25%
- Course project-30% - 2 Parts
- Class participation and attendance - 10%

PG

Grading and assessment:

- Homework - 10%
- Mid-term Exam-25%
- Final Exam-25%
- Course project-30% - 2 Parts
- Seminar presentation- 5%
- Class participation and attendance-5%

Course information

Mid-Term Exam

Week 6, 2 hours in-class

Final Exam

19 December (Week 14)

Course project

Week 6: Briefing

Week 13: Submission of report and presentation

Seminar Presentation by graduate students

Week 12

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Course information

Policies:

- Students are expected to attend all classes and lab sessions.
- Attendances for mid-term and final exams are compulsory.
- Assignments must be submitted on time. Late submission will not be accepted and graded.
- Active participation and interaction in the class and course project.

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Course information

- UG students-
- PG students-

Course Outline

- Nanoelectronics
- Nanotechnology

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Course information: Semiconductor Physics and MOSFETs

Reference Books

Device Physics

- "Fundamentals of Modern VLSI Devices" by Taur and Ning, Cambridge University Press
- "Solid State Electronic Devices" by Streetman and Banerjee
- "Fundamentals of Electronic Devices" by Achutan and Bhat, McGraw Hill
- "MOS (Metal Oxide Semiconductor) Physics and Technology" by E.H. Nicollian and J.R.Brews, Wiley Publishers.

Process Technology and Materials Characterization

- "Silicon VLSI Technology" by Plummer, Deal, and Griffin
- "ULSI Technology" by S. M. Sze, McGraw Hill

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Weekly teaching contents

Week No.	Topic	Description
Week 1	Introduction to Nanoelectronics and nano-CMOS scaling	ITRS Roadmap for CMOS scaling for advanced technology nodes towards 5nm/3nm technology node and challenges for further scaling. Need for new concepts in nanoelectronic materials and devices. Importance of high-k gate dielectric and metal electrodes in nanoscale MOSFETs.
Week 2	Nanoscale MOSFET, FinFET and other emerging devices	Working principle, physics and electrical characterization of nanoscale MOSFETs. Theory and working principle of FinFET. Fabrication and characterization of nanoscale MOSFETs, FinFETs and scaling trend towards 5nm/3nm technology node.
Week 3	Thin film deposition techniques and cleanroom experiment 1	Review of physical vapour deposition (PVD), chemical vapour deposition (CVD). Atomic layer deposition (ALD) and electron –beam evaporation method. Cleanroom experiment 1 (2nd class)-Growth of gate dielectric on silicon substrate.

Week 4	Nanofabrication techniques/methods	Extreme UV lithography, electron-beam lithography and nanopatterning, Self-aligned multiple patterning (SAMP) process solution for advanced CMOS technology nodes. Self-aligned double patterning (SADP) and self-aligned quadruple patterning (SAQP) processes.
Week 5	Reliability and failure analysis of nanoelectronic materials and devices	Study of key reliability and failure issues in nanoelectronic devices: process-induced defects, self-heating, carrier scattering, hot-carrier transport, dielectric degradation and breakdown.
Week 6	Interconnect technology	Interconnect technology, impact of scaling of CMOS devices on interconnects, reliability and failure mechanism in interconnects. Emerging interconnect technologies. Cleanroom experiment 2 (2nd class)- electron beam lithography and nanopatterning.

Week No.	Topic	Description
Week 8	Three dimensional integrated circuit (3D-IC) systems and technology	3D integration circuit technology, heterogeneous 3D IC systems and design challenges. Electrical probing experiment 3 (2^{nd} class)- electrical characterization of nanoscale devices.
Week 9	Understanding of Quantum mechanics : Carrier transport and application of quantum mechanics in nanoscale electronic devices	Electronic bond structure, electron transport, carrier scattering, coulomb blockade and quantum confinement in low-dimensional structures and nanoscale electronic devices
Week 10	Nanoscale characterization using scanning probe microscopy (SPM) techniques	Working principle of scanning tunneling microscopy (STM), atomic force microscopy (AFM) and its applications for analysing properties of nanoscale materials and devices.

Week 11	Nanoscale analysis using electron microscopy techniques	Scanning electron microscopy (SEM) and transmission electron microscopy (TEM analysis of nanoscale materials and devices. Study of SEM-STM nanoprobing and in-situ TEM characterization.
Week 12	Non-volatile memory (NVM) technology	Review of memory technologies. NAND-flash NVM technology and its scaling. Vertical (3D) NAND flash technology and emerging NVM devices such as resistive random-access memory (RRAM) and magnetic RAM (MRAM).
Week 13	Applications of nanomaterials and nanoelectronic devices	Applications of nanomaterials and nanoelectronic devices in different fields of nanoelectronics and nanotechnology. (a) Oxide and 2D-hexagonal boron nitride based RRAM devices for neuromorphic computing (b) 2D-graphene based logic devices (c) Energy technology (d) High-power and automobile application
Week 14	Review session – class 1	Review session – class 1

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Course Project Term 7

01.119/99.503: Nanoelectronics and Technology

Part 1: Application of AI in IC manufacturing

More details in Week 3

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Course Project Term 7

01.119/99.503: Nanoelectronics and Technology

1. Fabrication of MOS capacitor

- Select highly doped Silicon substrate
- Deposition of Silicon dioxide (SiO_2) and HK dielectric (10 nm)
- Deposition of Al (aluminium) metal electrode
- MOSCAP structures with different sizes using given mask.
- If required backside metal deposition for better Si substrate contact

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2. Electrical characterizatio of MOS capacitor

- I_g-V_g , initial I_g –time characteristics
- Analyse leakage current
- Find the Breakdown voltage of SiO_2
- I_g –time characteristics for soft breakdown and hard breakdown
- Analyse any other characteristics of the MOS capacitor

3. Simulation study of MOS capacitor

- C-V characteristics
- Correlation to experimental results

MOS cap tool: https://nanohub.org/resources/moscap

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Introduction lecture: Nanoelectronics

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Nanotechnology

- Nanotechnology- Products created with building blocks at length scale <100nm

  - There is a tremendous activities going on in the field of Nanotechnology
  - Nanoelectronics is one of the most mature of the nanotechnologies
  - Nanoelectronics growth in the future relies on innovations in the new materials and device structures

Ref: N. Bhat, CeNSE, IISc Bangalore- Nanoelectronic Device Technology

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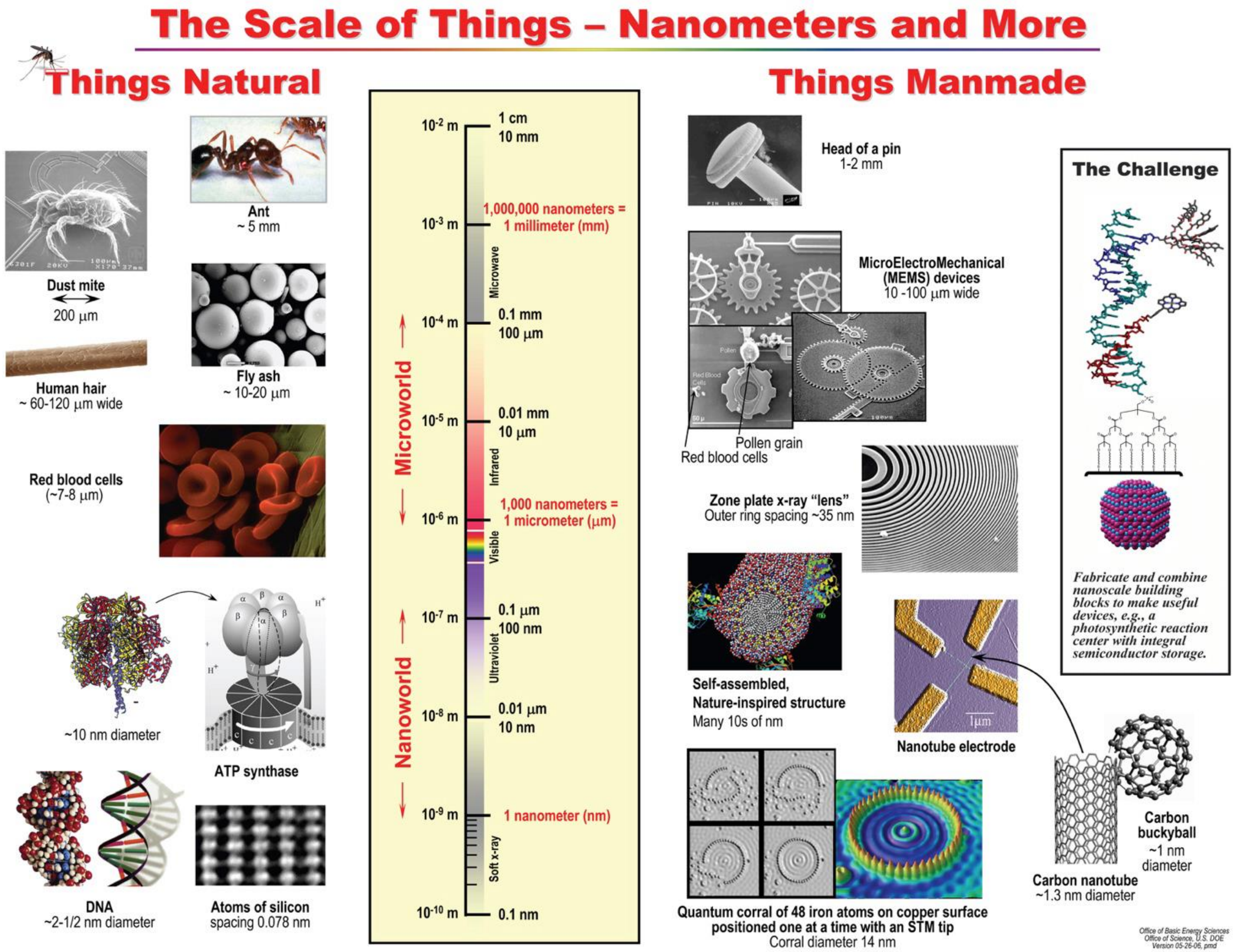
Nanotechnology: Size and scale



Ref: A Compar ison of Scale: Macro, Micr o, Nano-*Office of Basic Energy Sciences, U.S. DOE*
National Nanotechnological Initiative

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Nanotechnology Areas

- Nano-medicine and Bio- engineering
- Nano-robots
- Nano-MEMS
- Nanotechnology for energy applications
- Military applications
- Textile
- Nanoelectronics and etc

Ref: NANOTECHNOLOGY AND IT'S APPLICATIONS-Chinmoy Paul

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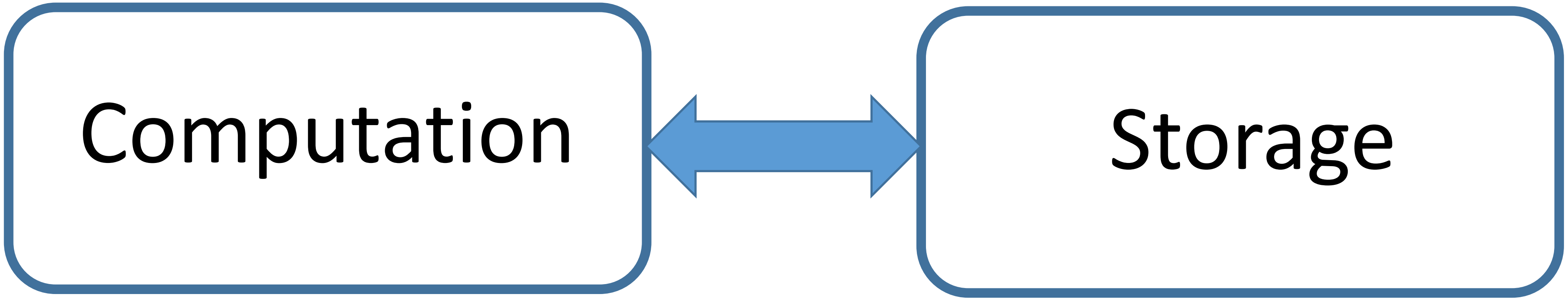
Nanoelectronics

- One of the major and successful technologies of Nanotechnology
- It involves very small scale (nanoscale) devices
- Highly scalable devices (Moore’s Law)
- Nanoelectronic devices consume less power and operates at low voltage
- Interface and Integration on a single chip
- Semiconductor Industry is driven by Nanoelectronic semconductor devices

Ref: https://www.slideshare.net/AakankshaR/nanoelectronics-63718699

Electronics: Big Picture



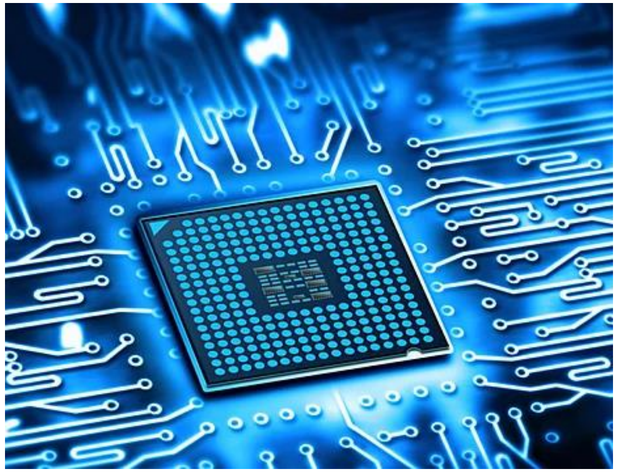
Microprocessors
Microcontrollers
DSP
Other processors

SRAM
DRAM
FLASH

Ref: N. Bhat, CeNSE, IISc Bangalore- Nanoelectronic Device Technology

Introduction to Semiconductor IC Manufacturing

Semiconductor IC (Integrated Circuit) manufacturing is a multi-step process to create microscopic electronic circuits on a semiconductor (mainly Silicon) wafer which forms the backbone of modern electronics.



https://www.outlookbusiness.com/columns/why-indias-semiconductor-future-needs-empowerment-not-red-tape

ICs are the foundational building blocks of virtually all modern electronic devices,

- driving economic growth, national security, and global competitiveness by enabling critical technologies in computing, communication, healthcare, and defense.
- fuels innovation in fields like artificial intelligence, the Internet of Things; leading to economic benefits and employment.

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Introduction to Semiconductor IC Manufacturing

- Global semiconductor market expected to surpass **$1 trillion by 2030**
- Key growth drivers: AI, IoT, 5G, automotive electronics, renewable energy
- Shift from planar CMOS to FinFET and GAA transistors

- Geopolitical factors influencing supply chain and manufacturing
- Regional investments: US, EU, China, and Southeast Asia

https://www.semiconductors.org/industry-impact/

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History of BJT and MOSFET

1. **Bipolar Junction Transistor (BJT)**

- **1947:** The first point-contact transistor was invented by **John Bardeen, Walter Brattain, and William Shockley** at Bell Labs (Nobel Prize in Physics, 1956).
- **1948–1950:** Shockley proposed and developed the **junction transistor** (p–n–p and n–p–n structures), leading to the practical BJT.
- **1950s:** First **commercial BJTs** appeared, replacing bulky vacuum tubes in hearing aids, radios, and early computers.
- **1950s–1960s:** BJTs became the backbone of electronics (radios, amplifiers, mainframe computers).
- **1960s:** First **integrated circuits (ICs)** used BJTs
- **1970s:** BJTs were dominant in **analog circuits** (amplifiers, audio, RF).

Modern Role

- Still used in:
  - **Analog/RF amplifiers** (higher gain, better linearity).
  - **Power electronics** (though often replaced by MOSFETs/IGBTs).
- Less common in digital logic (CMOS displaced BJT-based TTL).

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History of BJT and MOSFET

2. <u>Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET)</u>

- **1925–1930s:** Field-effect transistor concept was proposed by **Julius Lilienfeld** and **Oskar Heil.**
- **1959:** First successful **MOSFET** was demonstrated by **Mohamed Atalla and Dawon Kahng** at Bell Labs.
  - Used **Si-SiO_2 gate dielectric**, which solved the surface states problem.
  - MOSFET structure was simpler, scalable, and consumed less power than BJTs.
- **1960s:** MOSFET entered production; NMOS and PMOS logic families introduced.
- **1970s: CMOS (Complementary MOS)** developed by Frank Wanlass (1963 concept, commercialized in 1970s). **CMOS drastically reduced static power consumption → foundation of modern ICs.**
- **Intel 4004 (1971):** First commercial microprocessor, built using MOS technology.
- **Scaling & Dominance**
  - **1980s–2000s:** CMOS scaling (Moore's Law) enabled exponential transistor density growth.
  - **2010s:** MOSFET evolved into **FinFETs** (Intel 22nm, 2011).
  - MOSFETs dominate **digital electronics** (processors, memory, logic ICs).

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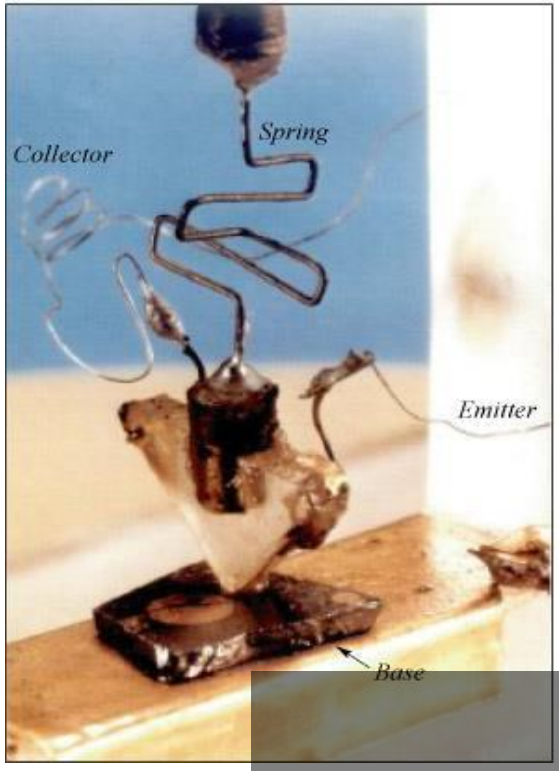
The first Transistor

- Made of Germanium semiconductor.
- Replacing bulky vacuum tubes.

The first point contact transistor
William Shockley, John Bardeen, and Walter Brattain
Bell Laboratories, Murray Hill, New Jersey (1947)



Courtesy of Lucent Technologies

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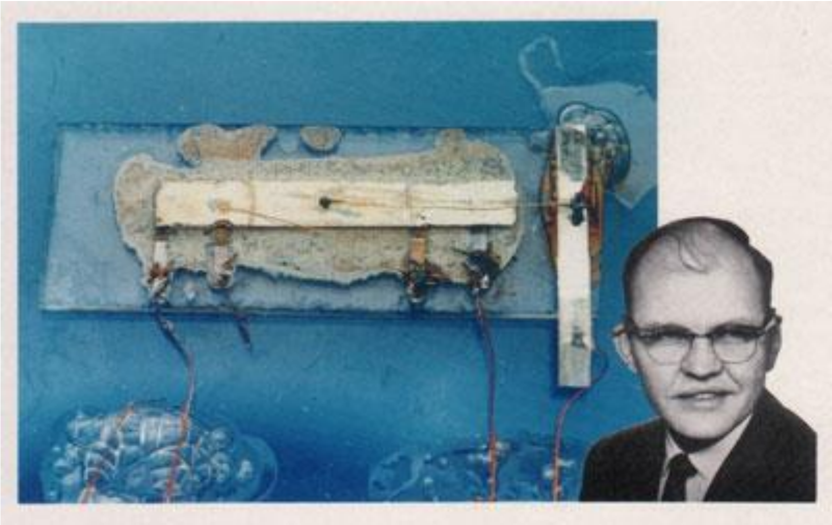
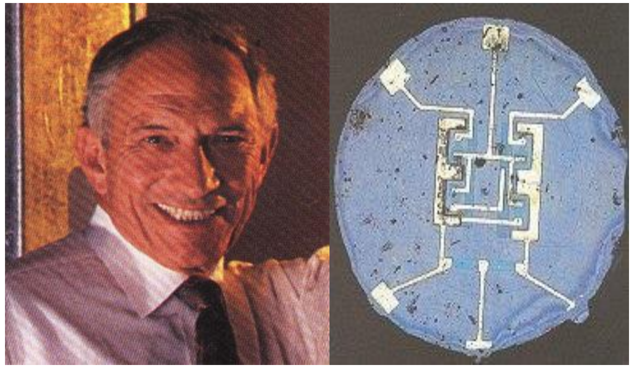
The First IC

- The first IC by Jack Kilby in 1958.
- Made on a small piece of germanium (not silicon).
- Contained a single transistor, a capacitor, and some resistors wired together by fine gold wires.
- Earned Jack Kilby the Nobel Prize in Physics (2000).



www.computerhistory.org/tdih/March/24



Robert Noyce and his first IC

- The first monolithic IC by Robert Noyce in 1959.
- Based on silicon planar process
- Instead of wiring components with external wires, Noyce used planar technology to create all components and their interconnections on a single piece of silicon.

https://www.chiphistory.org/monolithic-silicon-first-ic-chip

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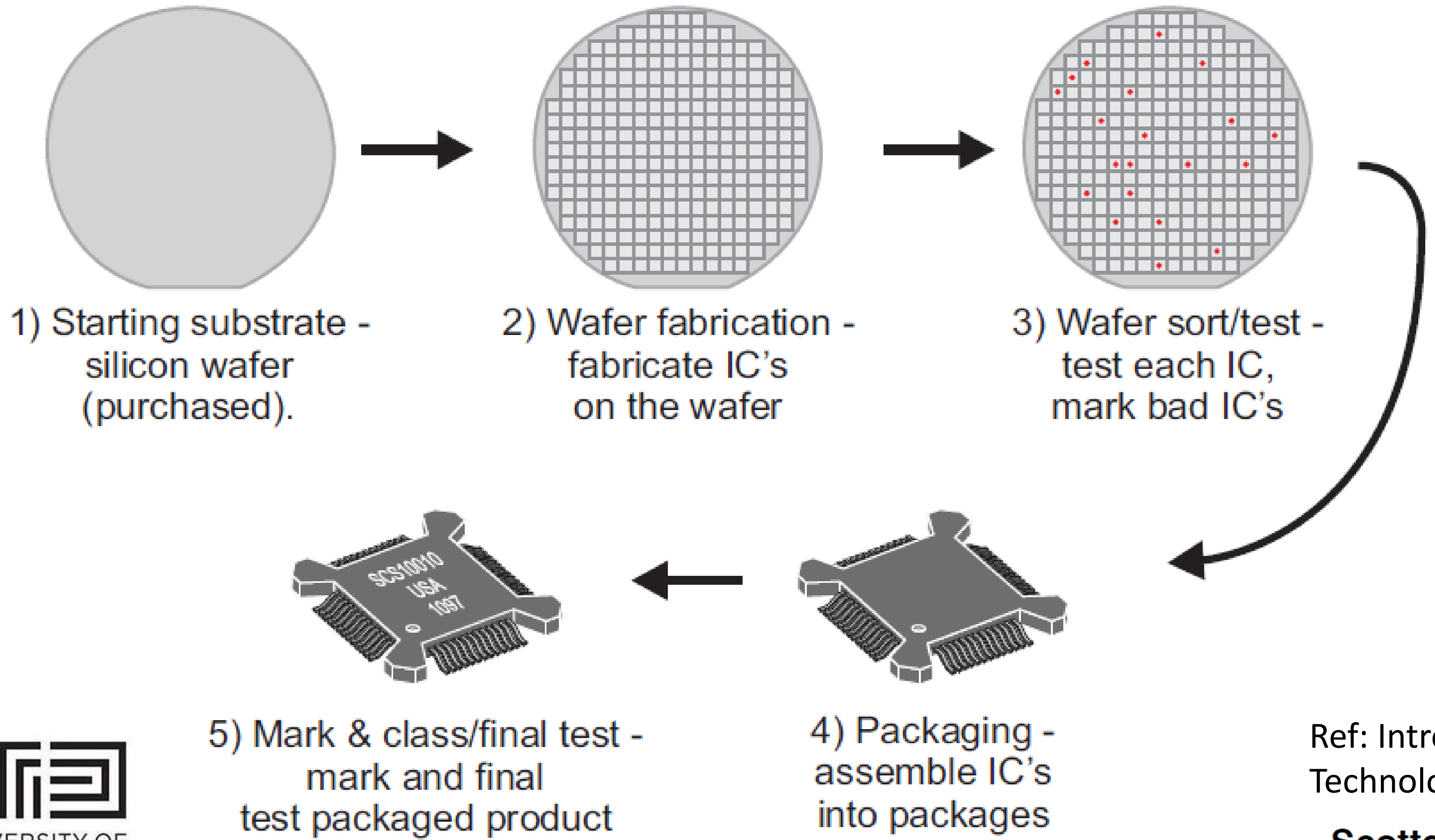
Moore's Law

The observation made in 1965 by Gordon Moore, co-founder of Intel, that the number of transistors per square inch on integrated circuits had doubled every 18 months since the integrated circuit was invented.

Moore predicted that this trend would continue for the foreseeable future. In subsequent years, the pace slowed, for the last few years the old definition of Moore Law is really related to transition to new process techniques and new materials,than measuring physical dimensions such as gate length or metal lines.

🗝 **Key Theme:**
The number of Transistors will
Double every 18 months on a chip

IC fabrication process



Ref: Introduction to IC Technology

Scotten W. Jones

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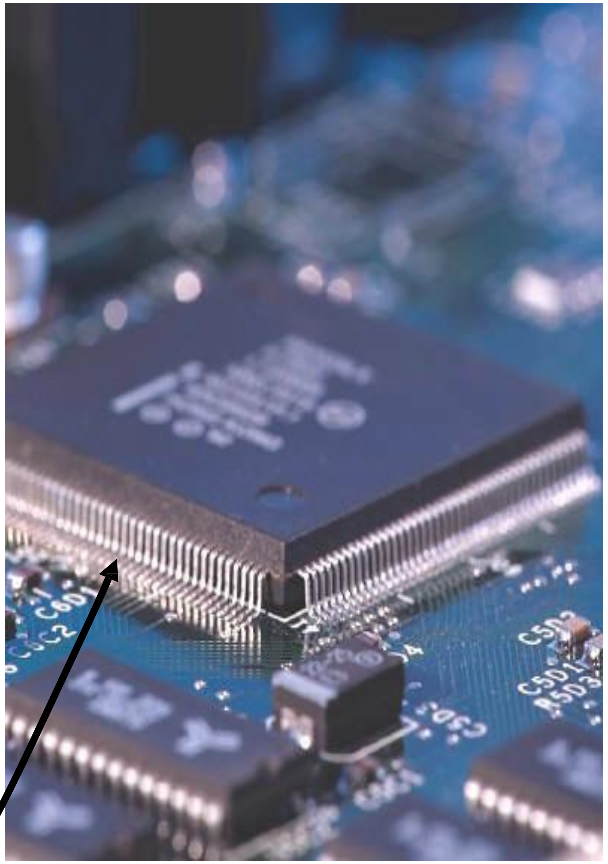
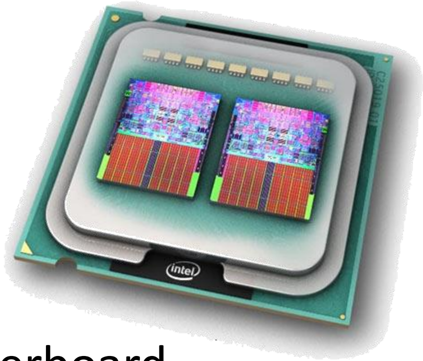
The Product



Surface mounted package on motherboard.

Pinned package for sockets.



Dual die, quad core package in land grid array, LGA.

Integrated Circuits

An integrated circuit is a small electronicdevice that contains billions of electronic components that perform an electronic function according to the laws of semiconductor physics

Advantages of IC's over discretes

- Smaller
- Use less power
- More reliable
- Perform better
- Cost less

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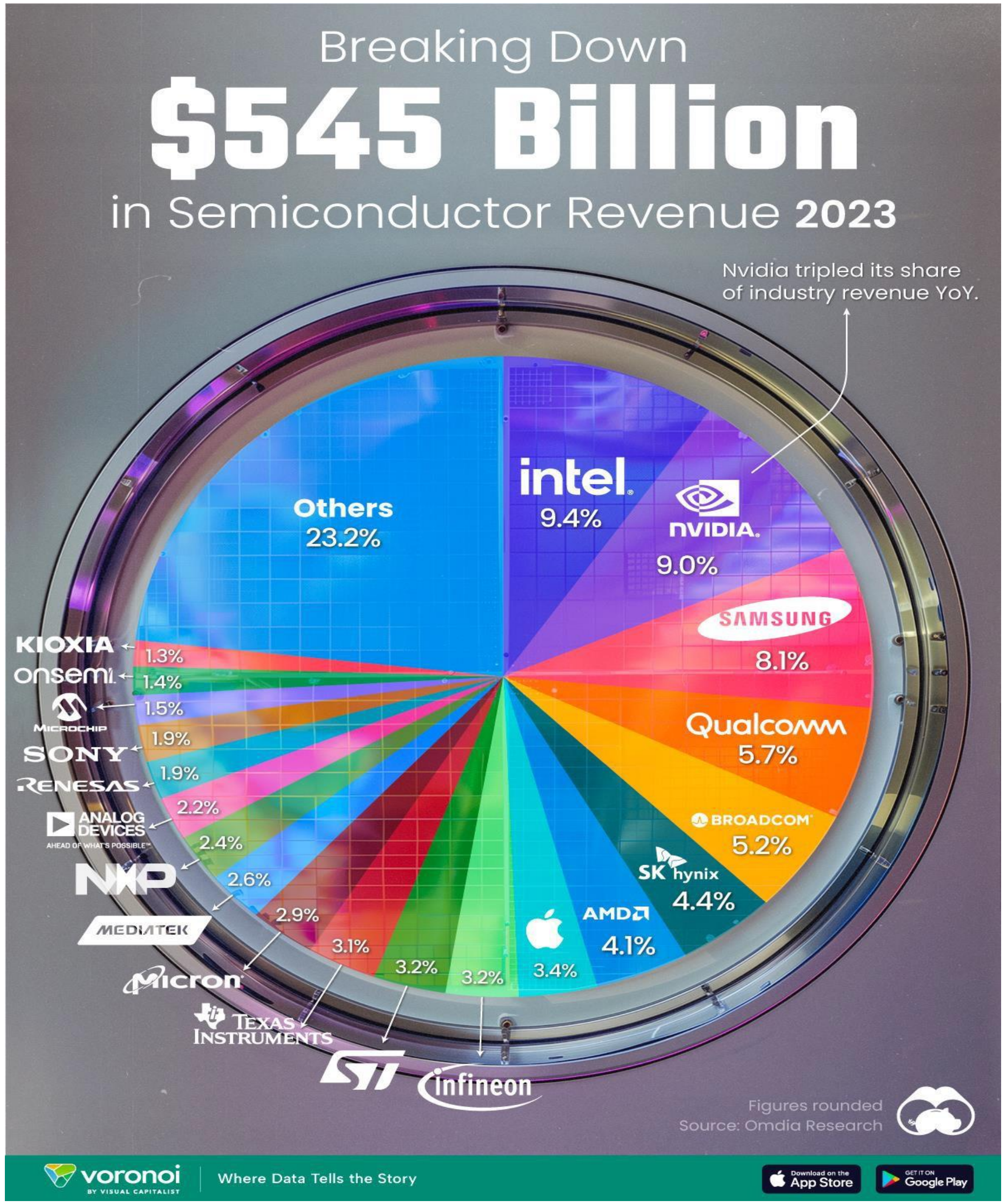
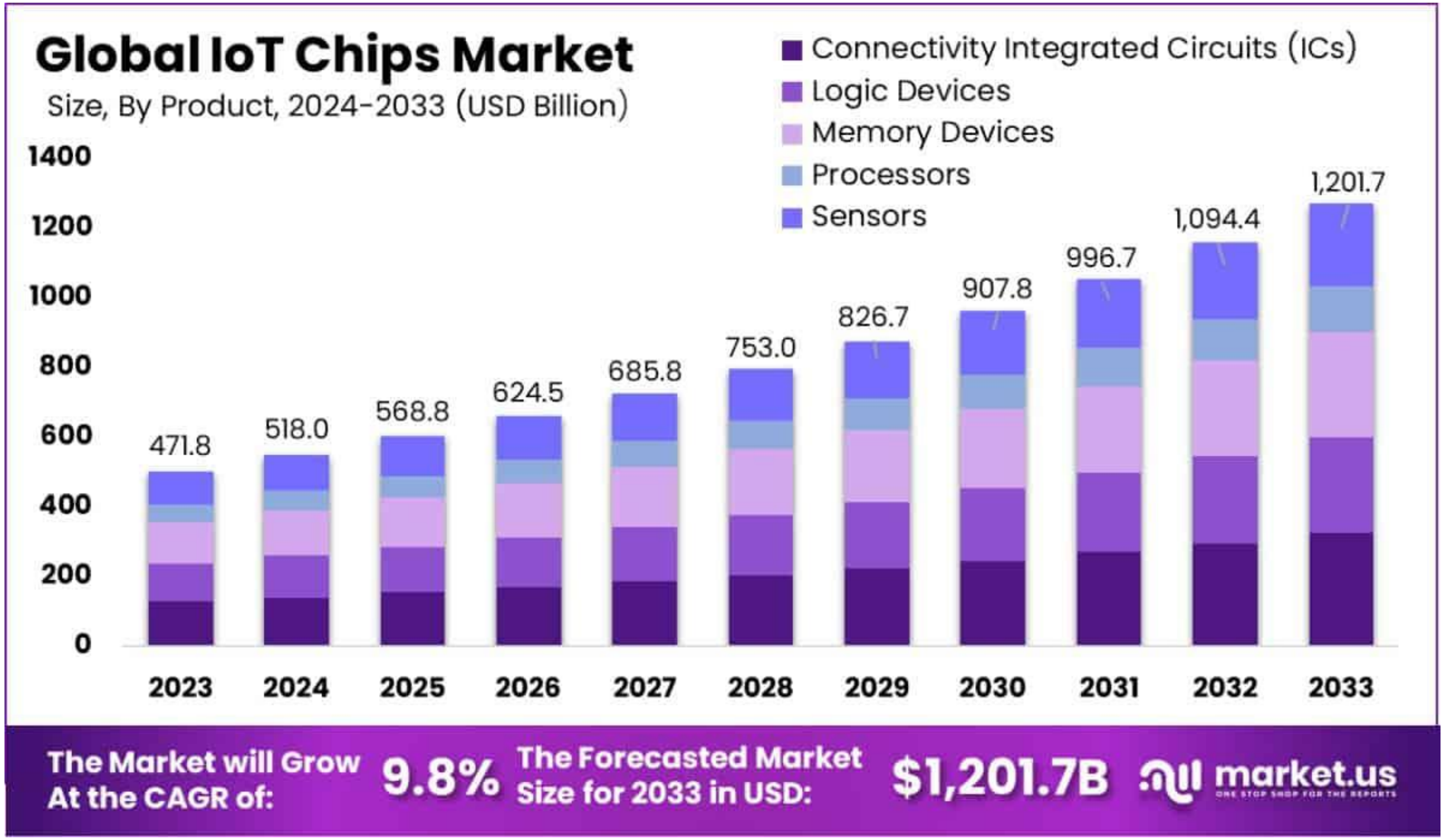


Semiconductor Technology, Devices and Applications



REF: https://market.us/report/iot-chips-market/

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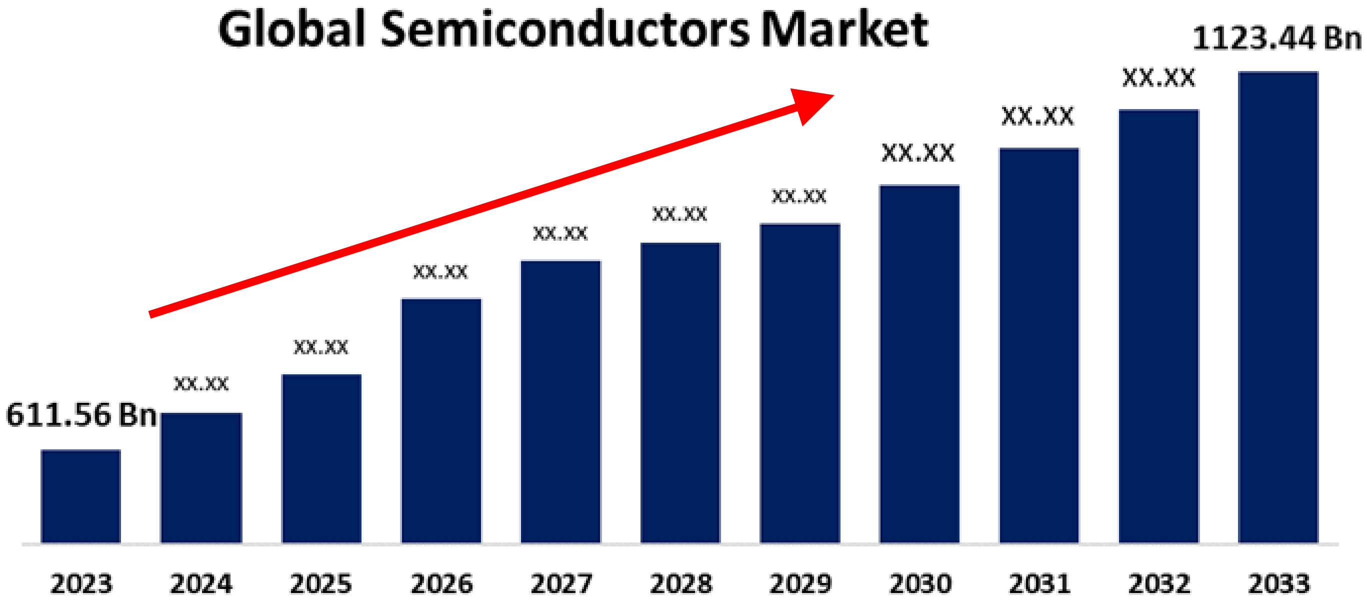
Market growth of Semiconductor Industry

The semiconductor market in the next decade is poised for significant transformation and growth, driven by technological advancements, increasing demand across various sectors.



https://www.sphericalinsights.com/reports/semiconductor-marke

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Applications: Semiconductor devices and ICs

REF: https://www.knowmade.com/knowmade-expertise/semiconductor-expertise/

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Semiconductor Supply Chain

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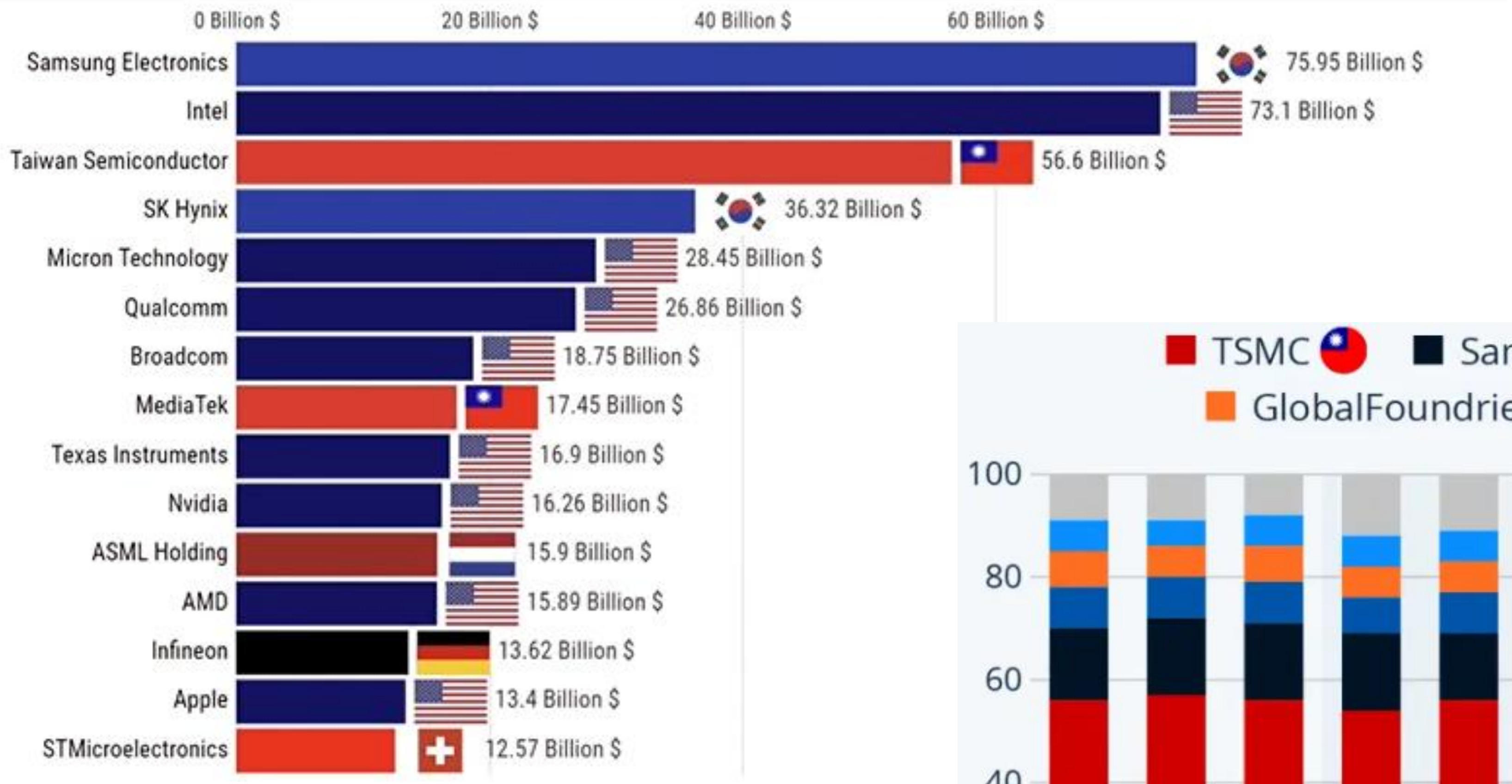
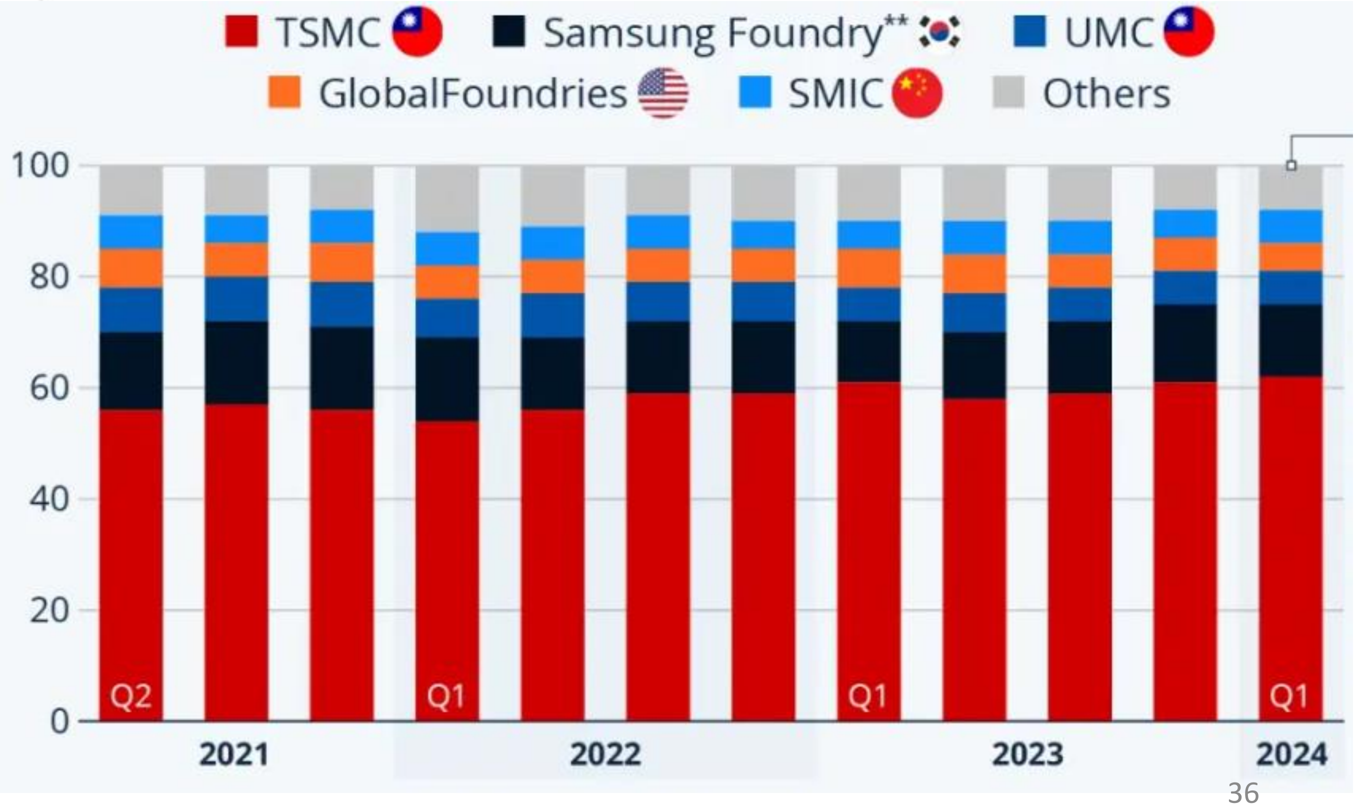
Ref: 30.538 – AiSeMAN, Naga, R SUTD Singapore

Top Semiconductor Companies





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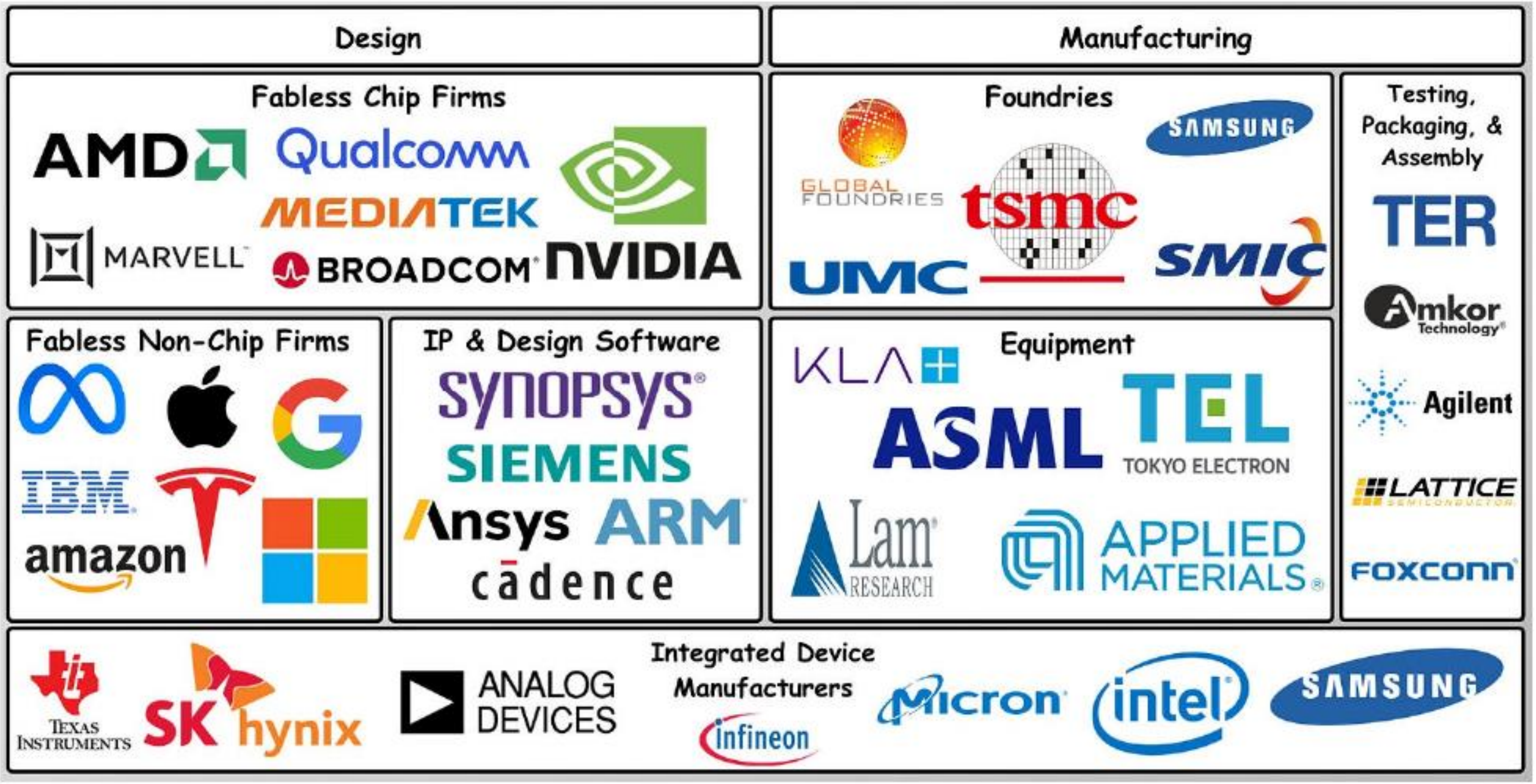
The Semiconductor Ecosystem



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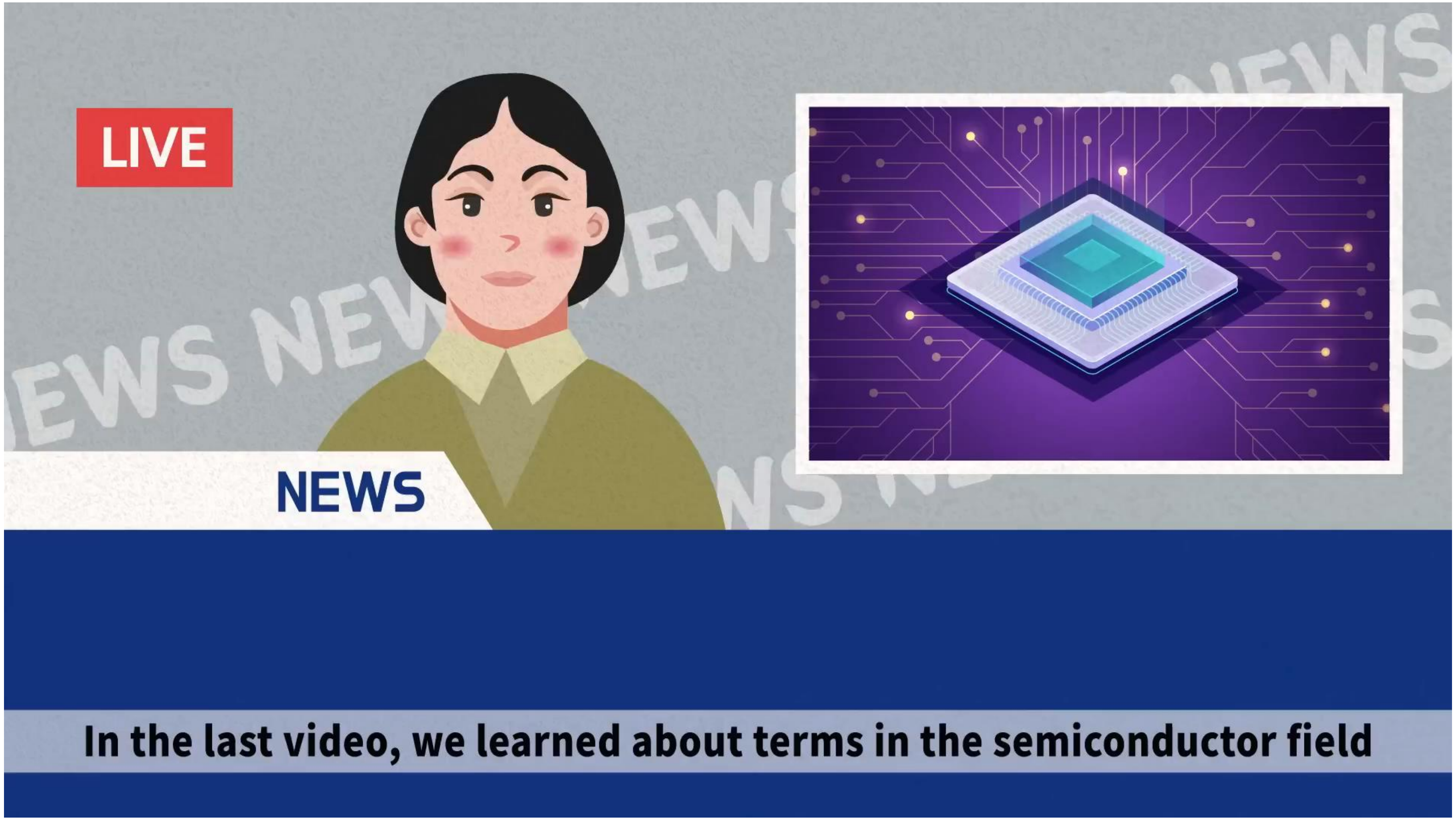
Ref: 30.538 – AiSeMAN, Naga, R SUTD Singapore

Semiconductor Ecosystem

https://www.youtube.com/watch?v=VJwnAaZw7Ac



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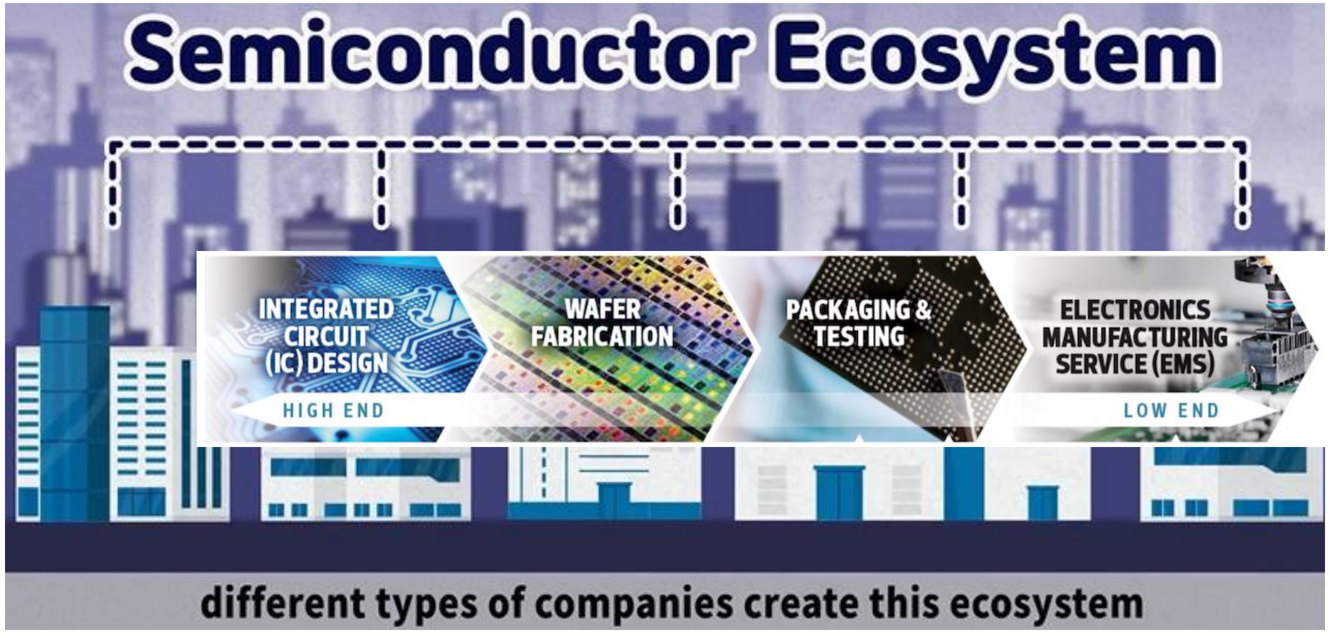
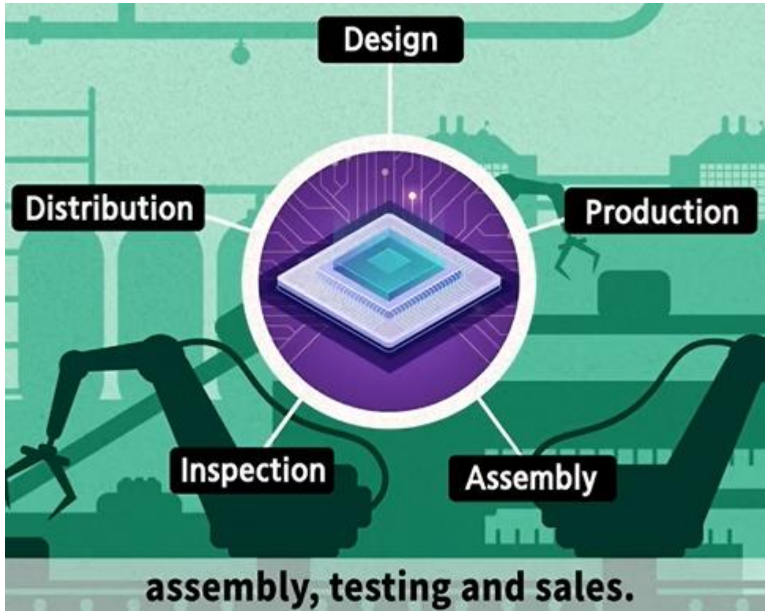
Semiconductor Ecosystem

- The semiconductor ecosystem is a network of companies that work together to develop and produce semiconductor devices/products. It includes companies that design, fabricate, test, and supply materials.





REF: https://www.nexteck.com.sg/snews/type86.html

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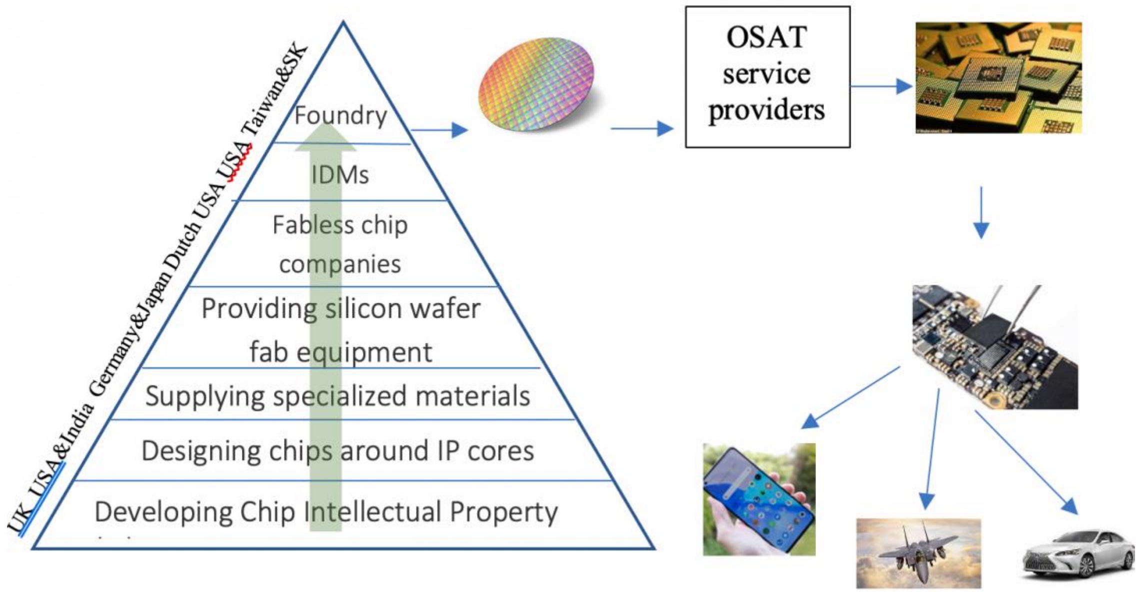
Semiconductor Ecosystem-Key Elements

- Raw Materials and Equipment Suppliers

- Design (Fabless Companies) (e.g., NVIDIA, Qualcomm, AMD) Use Electronic Design Automation (EDA) tools for designing integrated circuits (ICs).



- **Foundries (Fabrication Plants)**
  - Manufacture semiconductor chips based on designs provided by fabless companies (e.g., TSMC, Samsung Foundry, GlobalFoundries).
  - Handle advanced processes like extreme ultraviolet (EUV) lithography.

REF: https://www.the-waves.org/2022/03/17/semiconductor-value-chain-globally-distributed-ecosystem/

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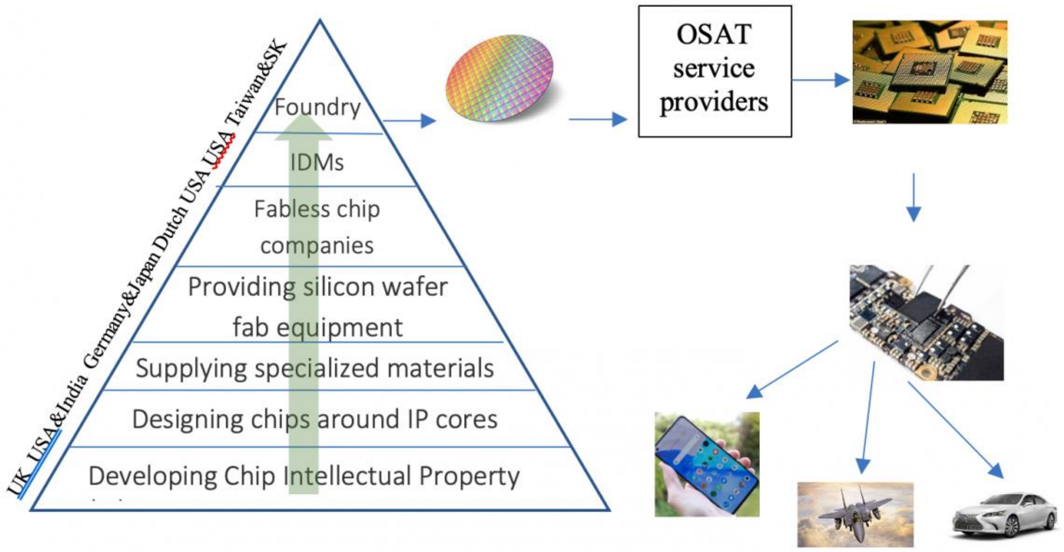
Semiconductor Ecosystem-Key Elements

- Integrated Device Manufacturers (IDMs)
  - Companies that design and manufacture their chips in-house (e.g., Intel, Samsung Electronics, Texas Instruments).
- Packaging and Testing
  - Encapsulate chips into protective packaging and test functionality.
  - Advanced packaging techniques
- include 3D stacking and chiplet integration.



- **Distribution and Supply Chain Management**
  - Logistics providers, distributors/sellers ensure chips reach end-users.
  - Includes addressing supply chain disruptions.
- **End-User Industries**

REF: https://www.the-waves.org/2022/03/17/semiconductor-value-chain-globally-distributed-ecosystem/

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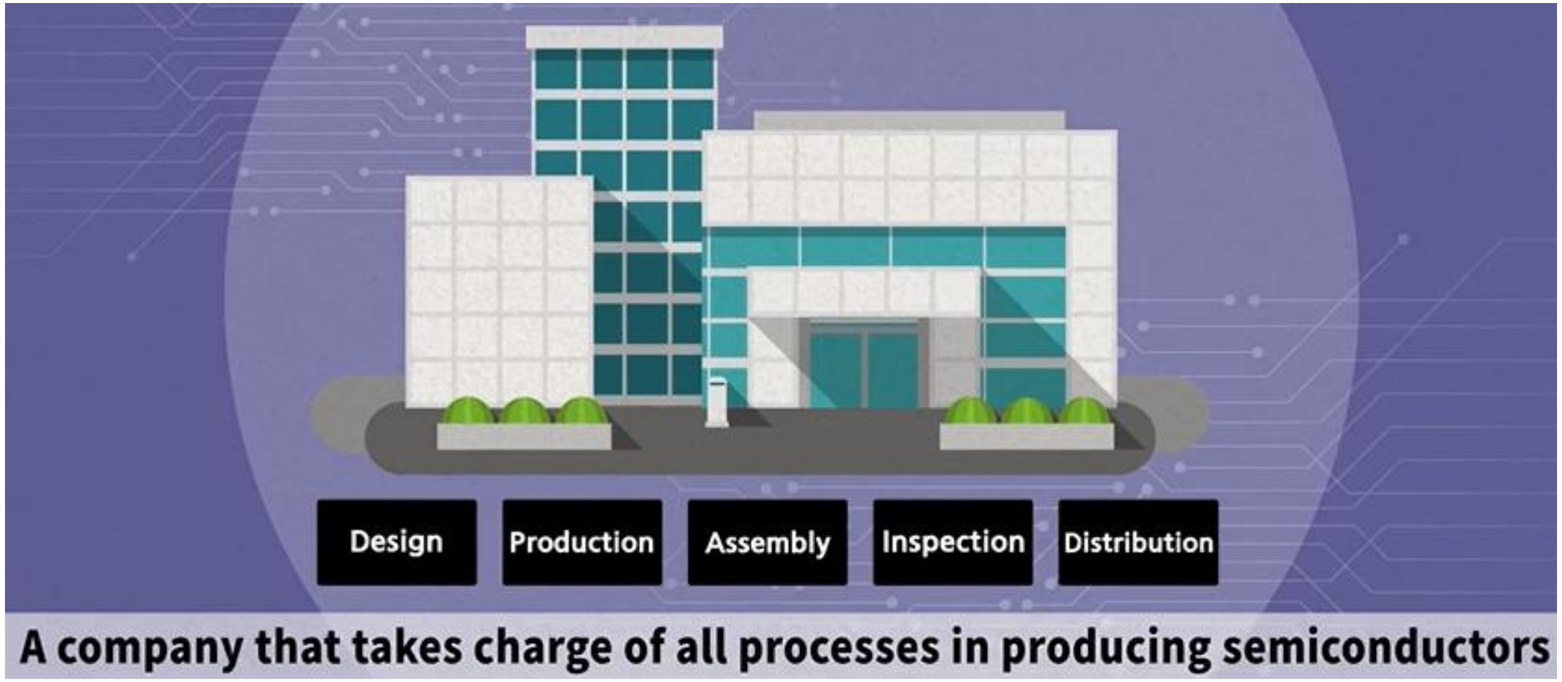
Types of Semiconductor Industries

- Integrated Device Manufacturers (IDMs)
- Companies that design and manufacture their chips in-house (e.g., Intel, Samsung Electronics).



REF: https://semiconductor.samsung.com/support/tools-resources/dictionary/semiconductor-glossary-integrated-device-manufacturer-idm/

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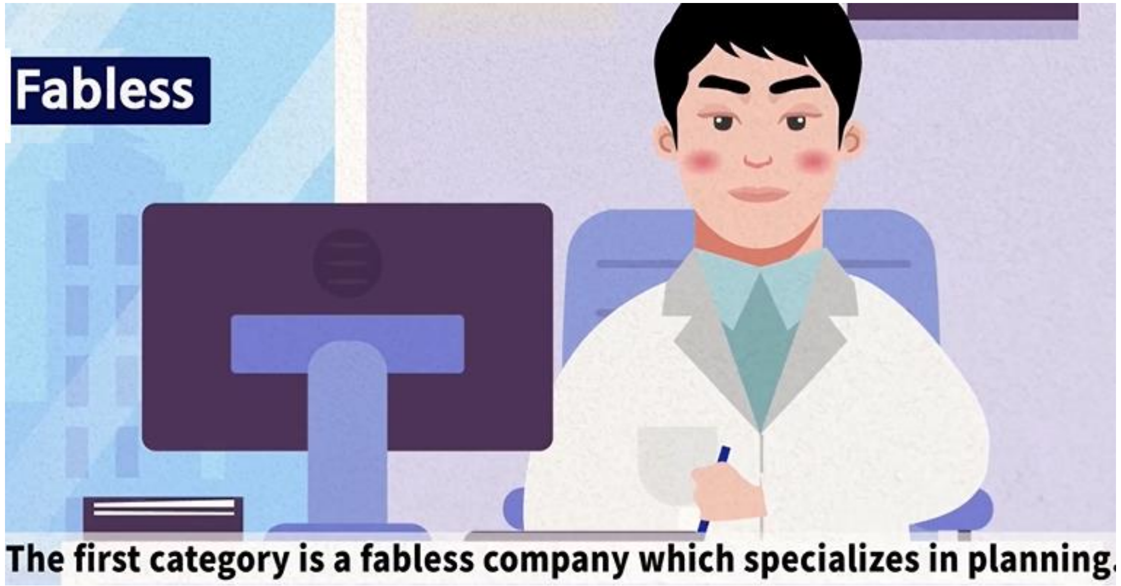
Types of Semiconductor Industries

- Fab-less companies: Nvidia,
- Qualcomm, AMD, Broadcom

- Specialize in designing chips,
- but outsource the actual
- manufacturing to third-party foundries.



- This business model allows them to focus on innovation and chip design while leveraging the advanced manufacturing capabilities of dedicated semiconductor foundries.

REF: https://semiconductor.samsung.com/support/tools-resources/dictionary/semiconductor-glossary-integrated-device-manufacturer-idm/

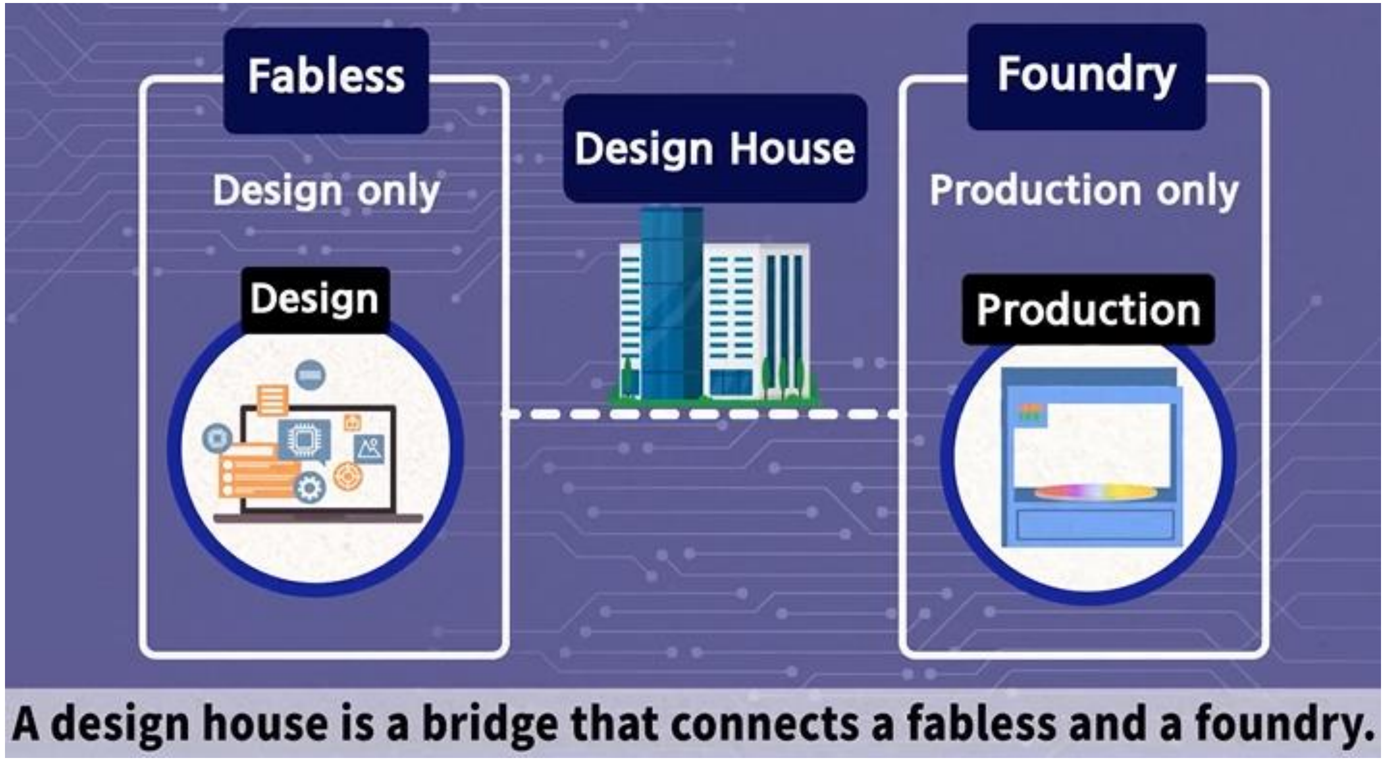
Types of Semiconductor Industries

- Manufacture semiconductor chips based on designs provided by fabless companies (e.g., TSMC, Samsung Foundry, GlobalFoundries).
- Handle advanced processes like extreme ultraviolet (EUV) lithography.

REF: https://semiconductor.samsung.com/support/tools-resources/dictionary/semiconductor-glossary-integrated-device-manufacturer-idm/

Types of Semiconductor Industries

- Design House-They act as a **bridge between product companies and foundries**, enabling rapid development without the need for in-house fabs.



REF: *https://semiconductor.samsung.com/support/tools-resources/dictionary/semiconductor-glossary-integrated-device-manufacturer-idm/*

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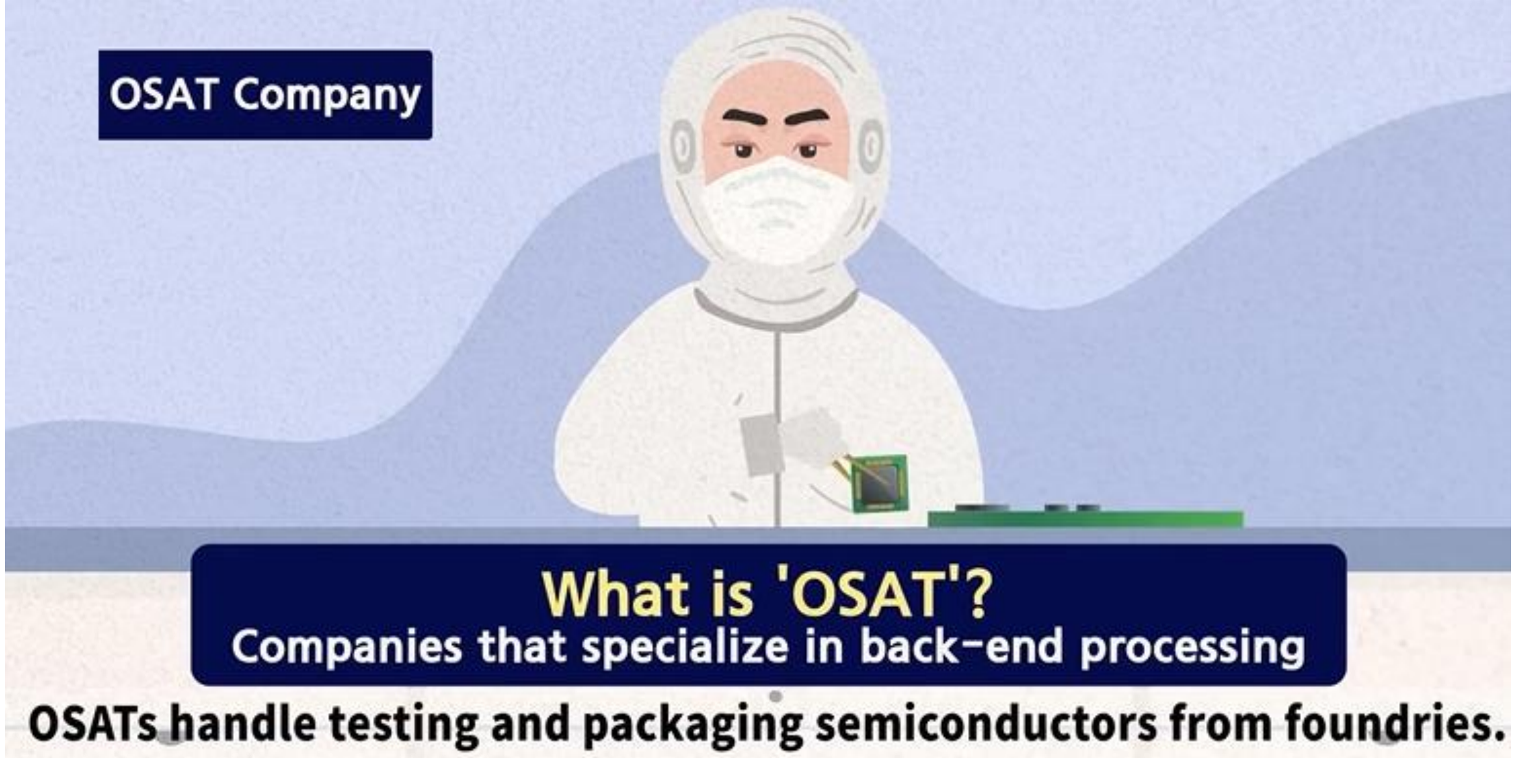
Types of Semiconductor Industries

- **OSAT:** Outsourced Semiconductor Assembly and Test (OSAT) companies are third-party businesses that perform assembly, packaging, and testing of semiconductors (Amkor Technology, ChipMOS Technologies)



REF: *https://semiconductor.samsung.com/support/tools-resources/dictionary/semiconductor-glossary-integrated-device-manufacturer-idm/*

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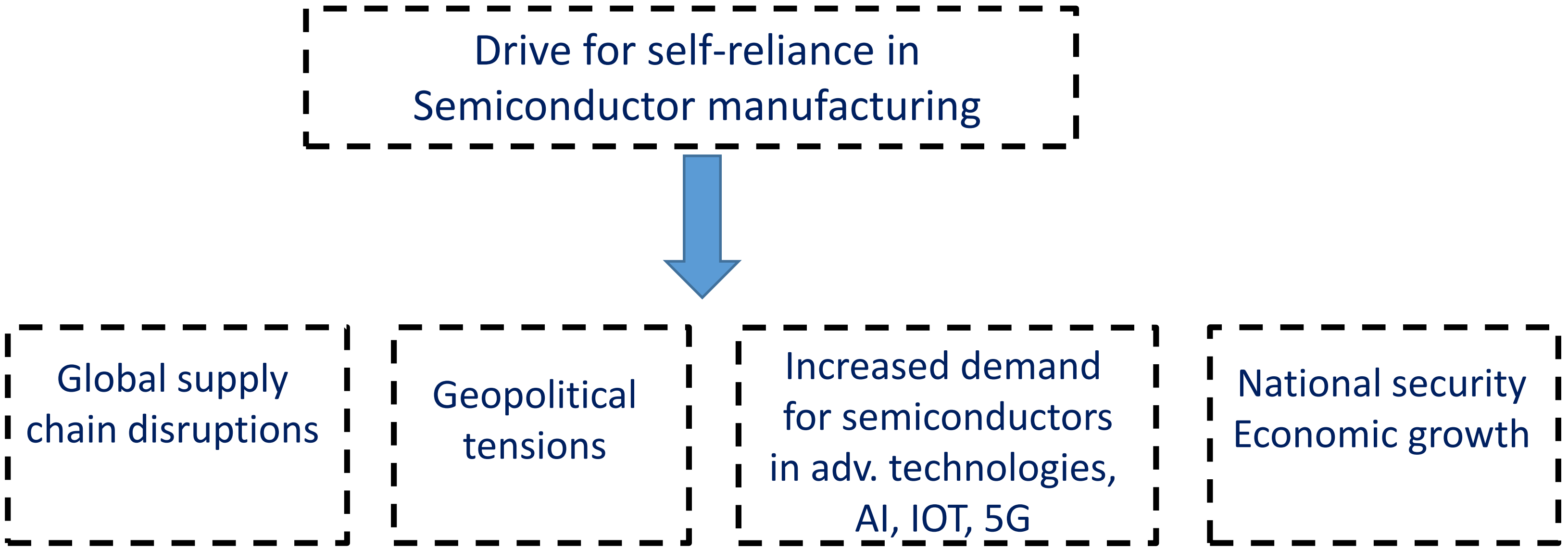
Self-Reliance in Semiconductor Manufacturing

- The semiconductor market in the next decade is poised for significant transformation and growth, driven by technological advancements, increasing demand across various sectors, in communications, computing, healthcare, transportation, and defense



Semiconductor Materials

- **Conductors**
- Gold
- Silver
- Copper
- Aluminum
- Cobalt

- **Semiconductors**
- Germanium
- Silicon
- Gallium Arsenide
- Carbon
- SiC
- GaN

- **Non-Conductors**
- Glass (3.8k)
- Air (1k)
- Silicon Dioxide (3.9k)
- Silicon Nitride (7.5k)
- Hafnium Dioxide (30k)

A **dielectric material** is a substance

that is a poor conductor of electricity, but an efficient supporter of electrostatic fields.
The **dielectric constant** , the extent to which a substance concentrates the electrostatic lines of flux

A **low-k** dielectric has a value of 3.9 or lower and a **high-k** a value of 4 or higher

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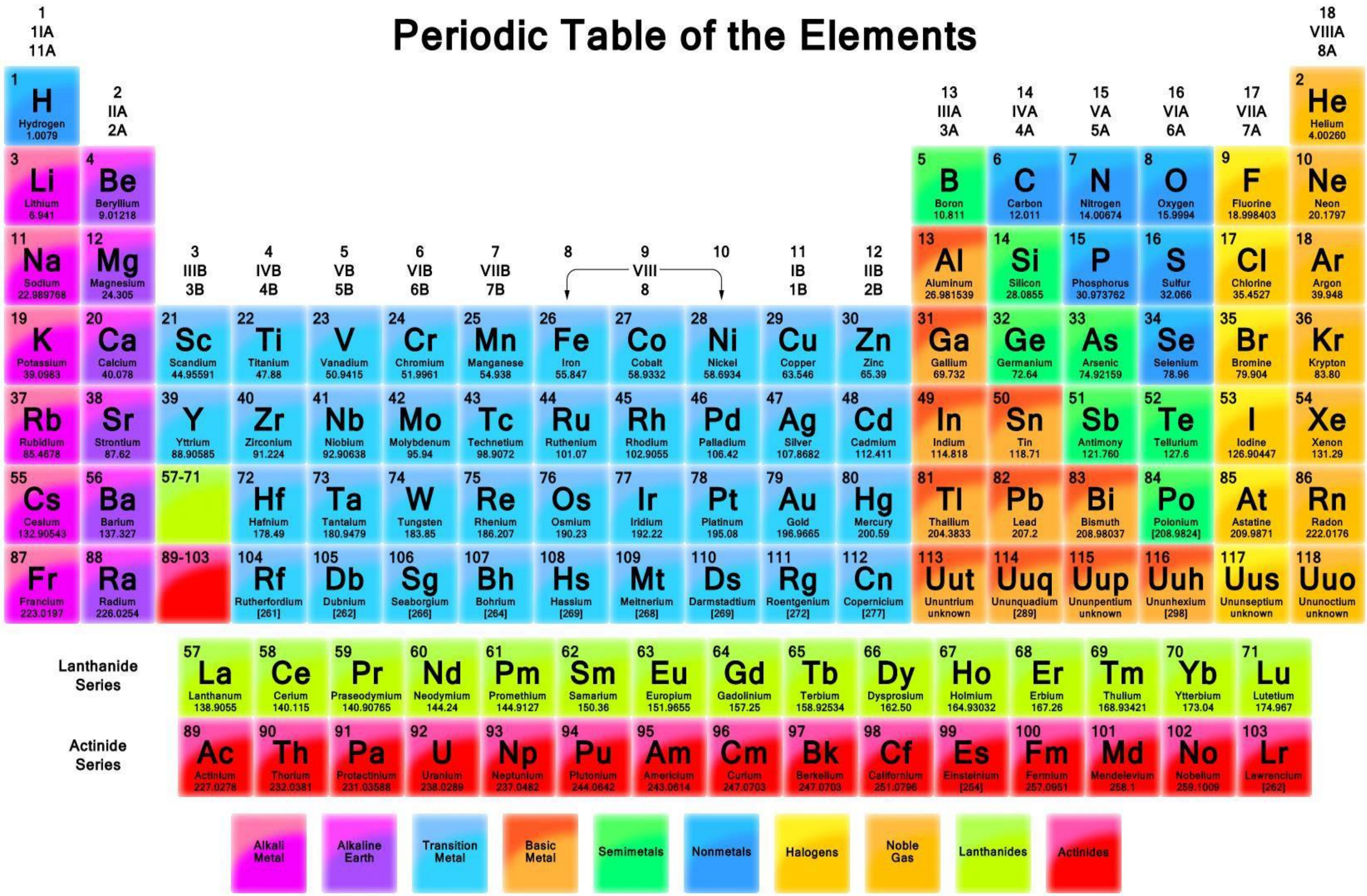

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Semiconductor Technology, Devices and Applications

Silicon- Semiconductor Technology

Logic Device

Planar CMOS
FinFETs
Nanosheet FETs
GAA-FETs

Memory

Volatile-RAM
Non-Volatile-Flash, RRAM, MRAM etc

Other applications

Analog, Power electronics, Display technology

III-V Semiconductor Technology

- High-frequency and high-speed electronic devices
- Lasers, photodetectors, and light-emitting diodes (LEDs)
- Sensors, frequency-converting devices, and the Internet of things

GaAs, InP, GaN etc

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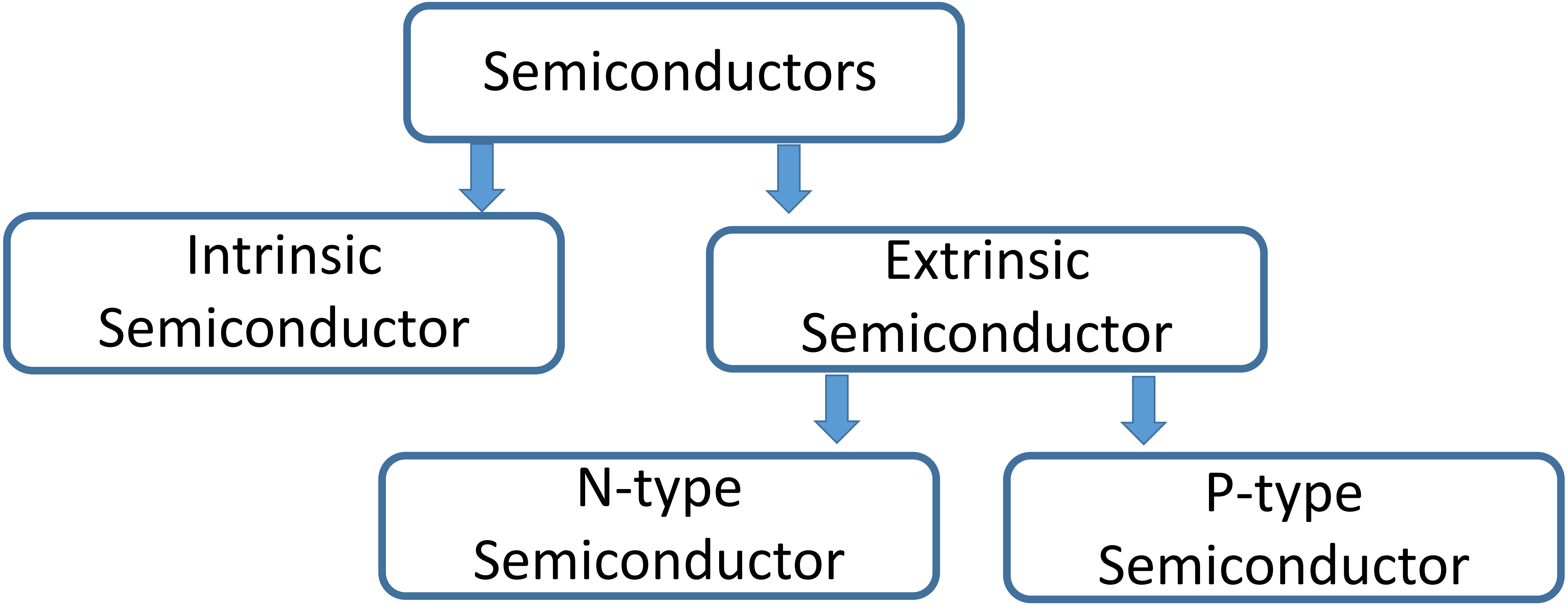
Review of Semiconductors



Nanoelectronics

- From Sand to Silicon: the Making of a Chip | Intel

https://www.youtube.com/watch?v=Q5paWn7bFg4

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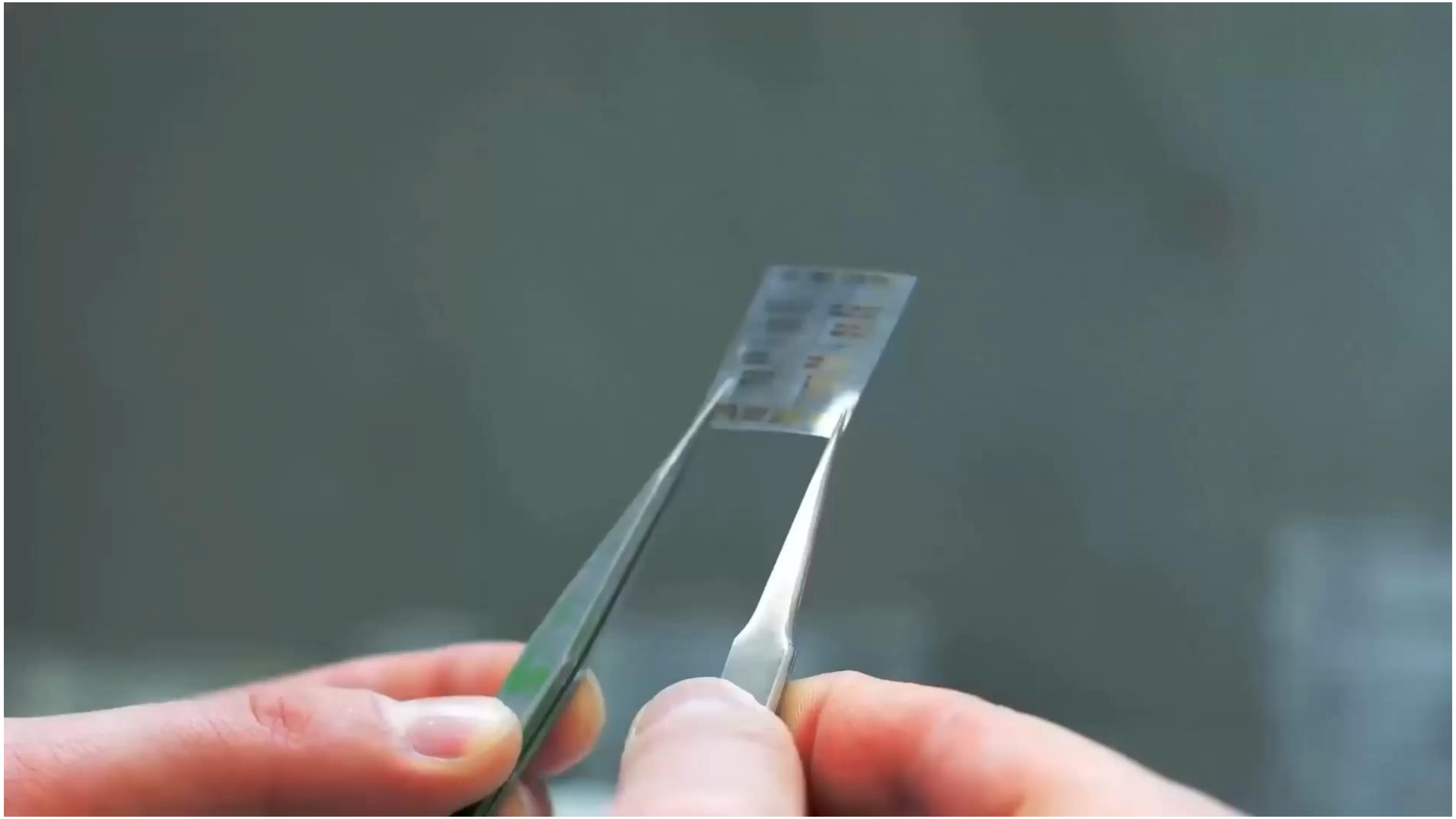
Nanoelectronics

https://www.youtube.com/watch?v=52GoRYP1les



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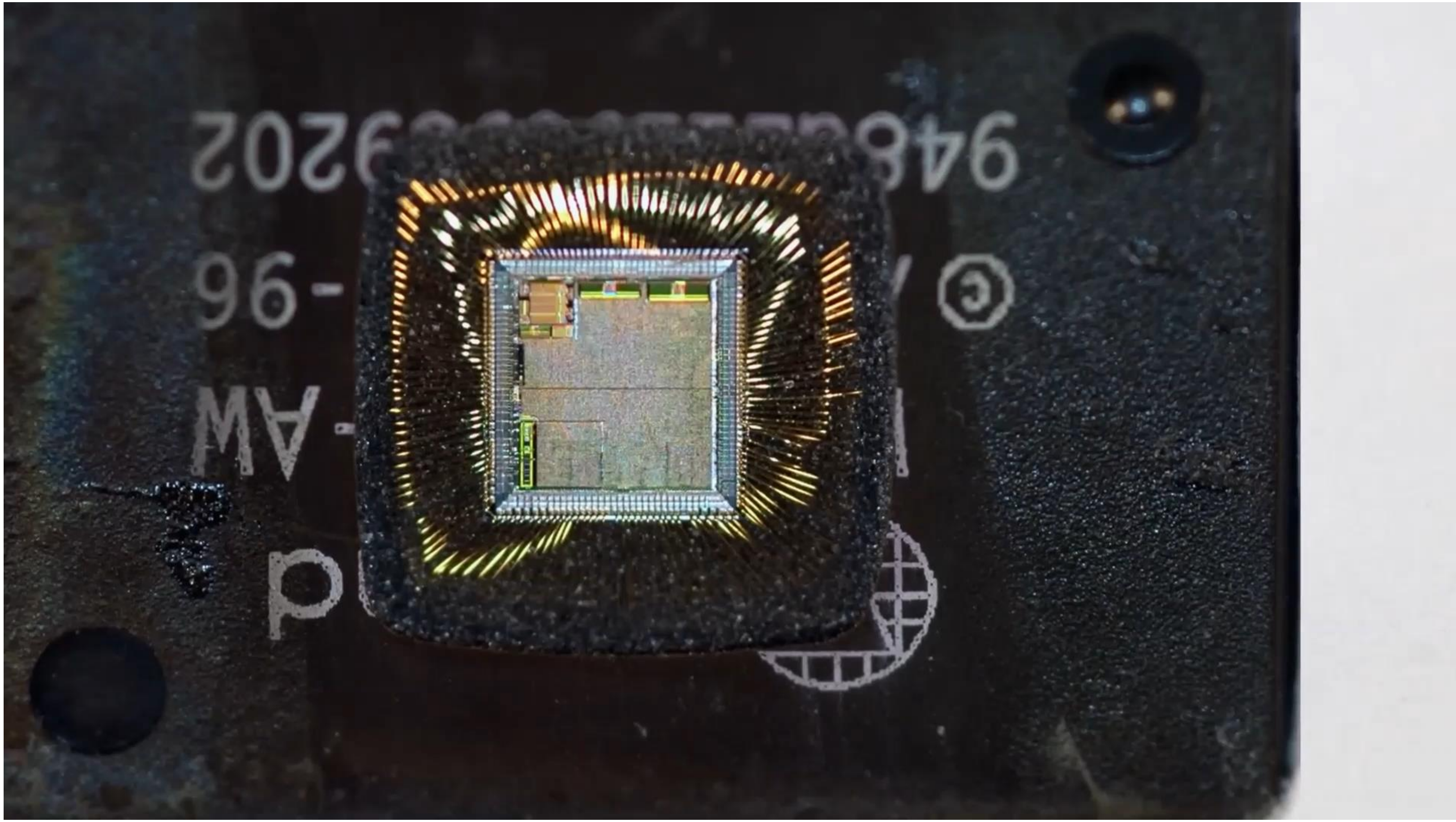
Nanoelectronics

https://www.youtube.com/results?search_query=Zoom+Into+a+Microchip+



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Nanoelectronics

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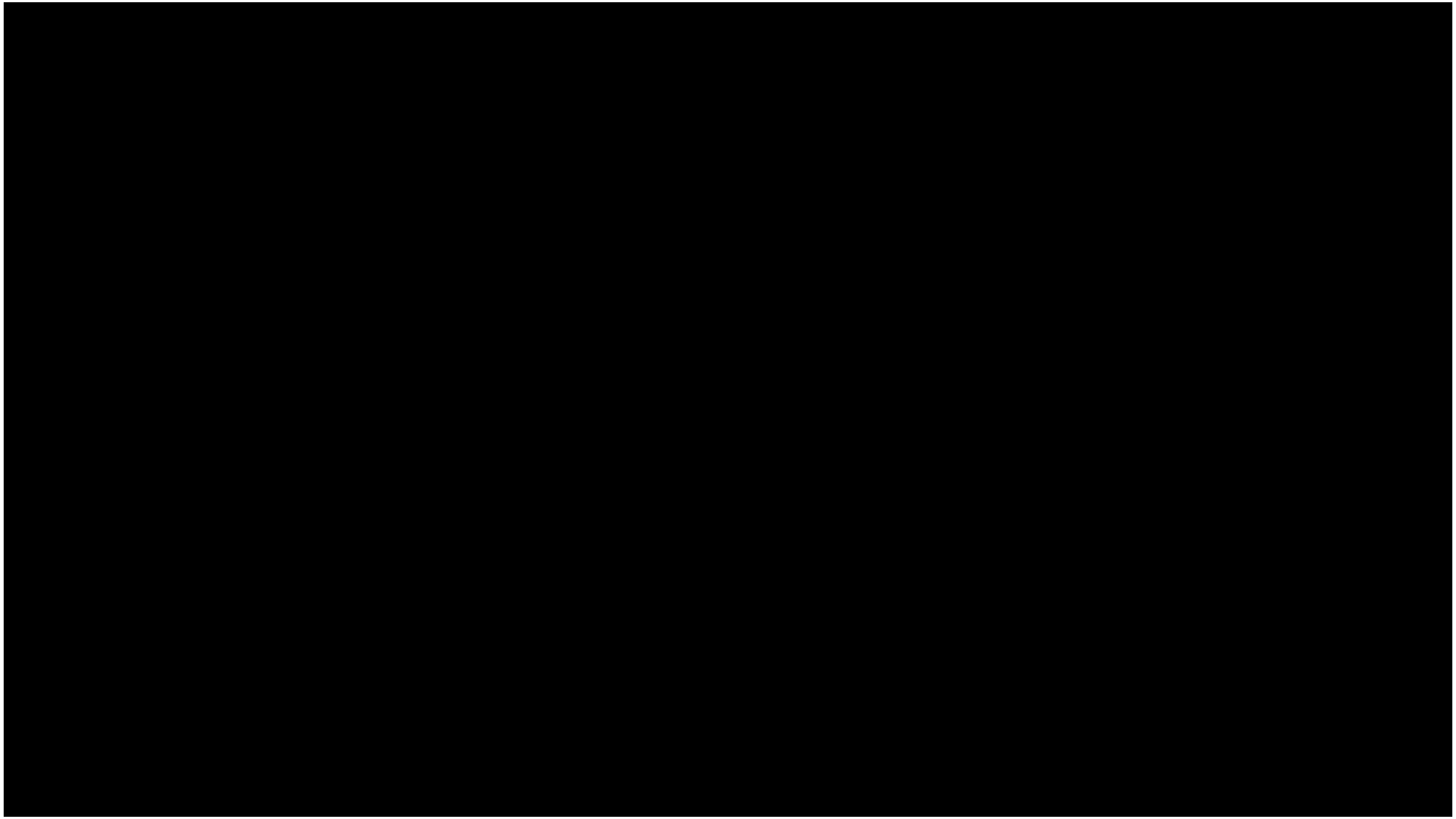

Semiconductor Materials

- **Conductors**
- Gold
- Silver
- Copper
- Aluminum
- Cobalt

- **Semiconductors**
- Germanium
- Silicon
- Gallium Arsenide
- Carbon
- SiC
- GaN

- **Non-Conductors**
- Glass (3.8k)
- Air (1k)
- Silicon Dioxide (3.9k)
- Silicon Nitride (7.5k)
- Hafnium Dioxide (30k)

A **dielectric material** is a substance

that is a poor conductor of electricity, but an efficient supporter of electrostatic fields.
The **dielectric constant** , the extent to which a substance concentrates the electrostatic lines of flux

A **low-k** dielectric has a value of 3.9 or lower and a **high-k** a value of 4 or higher

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Periodic Table of the Elements

1 1IA 11A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 **H** Hydrogen 1.0079																	2 **He** Helium 4.00260
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.01218											5 **B** Boron 10.811	6 **C** Carbon 12.011	7 **N** Nitrogen 14.00674	8 **O** Oxygen 15.9994	9 **F** Fluorine 18.998403	10 **Ne** Neon 20.1797
11 **Na** Sodium 22.989768	12 **Mg** Magnesium 24.305											13 **Al** Aluminum 26.981539	14 **Si** Silicon 28.0855	15 **P** Phosphorus 30.973762	16 **S** Sulfur 32.066	17 **Cl** Chlorine 35.4527	18 **Ar** Argon 39.948
19 **K** Potassium 39.0983	20 **Ca** Calcium 40.078	21 **Sc** Scandium 44.95591	22 **Ti** Titanium 47.88	23 **V** Vanadium 50.9415	24 **Cr** Chromium 51.9961	25 **Mn** Manganese 54.938	26 **Fe** Iron 55.847	27 **Co** Cobalt 58.9332	28 **Ni** Nickel 58.6934	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.732	32 **Ge** Germanium 72.64	33 **As** Arsenic 74.92159	34 **Se** Selenium 78.96	35 **Br** Bromine 79.904	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.4678	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.90585	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.90638	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium 98.9072	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.9055	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.8682	48 **Cd** Cadmium 112.411	49 **In** Indium 114.818	50 **Sn** Tin 118.71	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.6	53 **I** Iodine 126.90447	54 **Xe** Xenon 131.29
55 **Cs** Cesium 132.90543	56 **Ba** Barium 137.327	57-71	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.9479	74 **W** Tungsten 183.85	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.22	78 **Pt** Platinum 195.08	79 **Au** Gold 196.9665	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.3833	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98037	84 **Po** Polonium [208.9824]	85 **At** Astatine 209.9871	86 **Rn** Radon 222.0176
87 **Fr** Francium 223.0197	88 **Ra** Radium 226.0254	89-103	104 **Rf** Rutherfordium [261]	105 **Db** Dubnium [262]	106 **Sg** Seaborgium [266]	107 **Bh** Bohrium [264]	108 **Hs** Hassium [269]	109 **Mt** Meitnerium [268]	110 **Ds** Darmstadtium [269]	111 **Rg** Roentgenium [272]	112 **Cn** Copernicium [277]	113 **Uut** Ununtrium unknown	114 **Uuq** Ununquadium [289]	115 **Uup** Ununpentium unknown	116 **Uuh** Ununhexium [298]	117 **Uus** Ununseptium unknown	118 **Uuo** Ununoctium unknown

Lanthanide Series	57 **La** Lanthanum 138.9055	58 **Ce** Cerium 140.115	59 **Pr** Praseodymium 140.90765	60 **Nd** Neodymium 144.24	61 **Pm** Promethium 144.9127	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.9655	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.92534	66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93032	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.93421	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.967
Actinide Series	89 **Ac** Actinium 227.0278	90 **Th** Thorium 232.0381	91 **Pa** Protactinium 231.03588	92 **U** Uranium 238.0289	93 **Np** Neptunium 237.0482	94 **Pu** Plutonium 244.0642	95 **Am** Americium 243.0614	96 **Cm** Curium 247.0703	97 **Bk** Berkelium 247.0703	98 **Cf** Californium 251.0796	99 **Es** Einsteinium [254]	100 **Fm** Fermium 257.0951	101 **Md** Mendelevium 258.1	102 **No** Nobelium 259.1009	103 **Lr** Lawrencium [262]

Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Semimetals | Nonmetals | Halogens | Noble Gas | Lanthanides | Actinides

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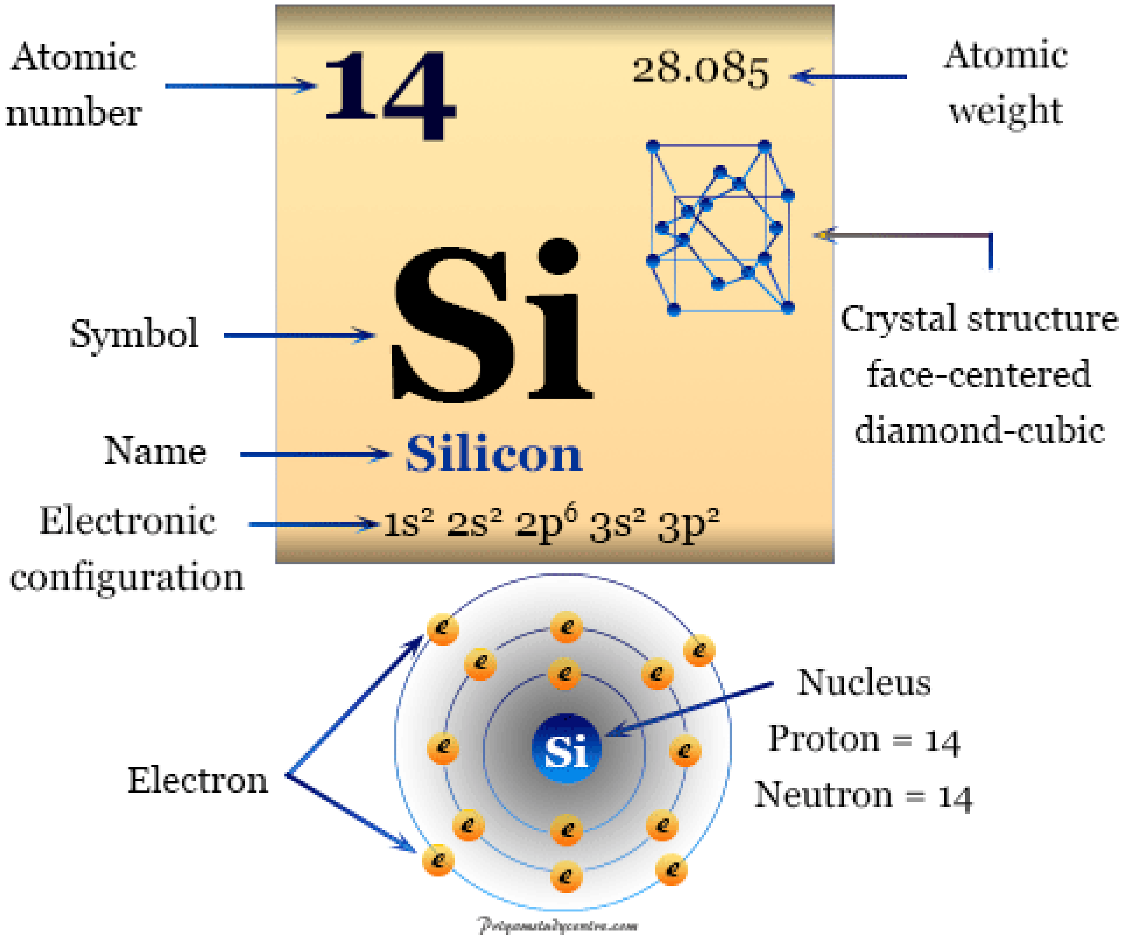
Silicon Semiconductor



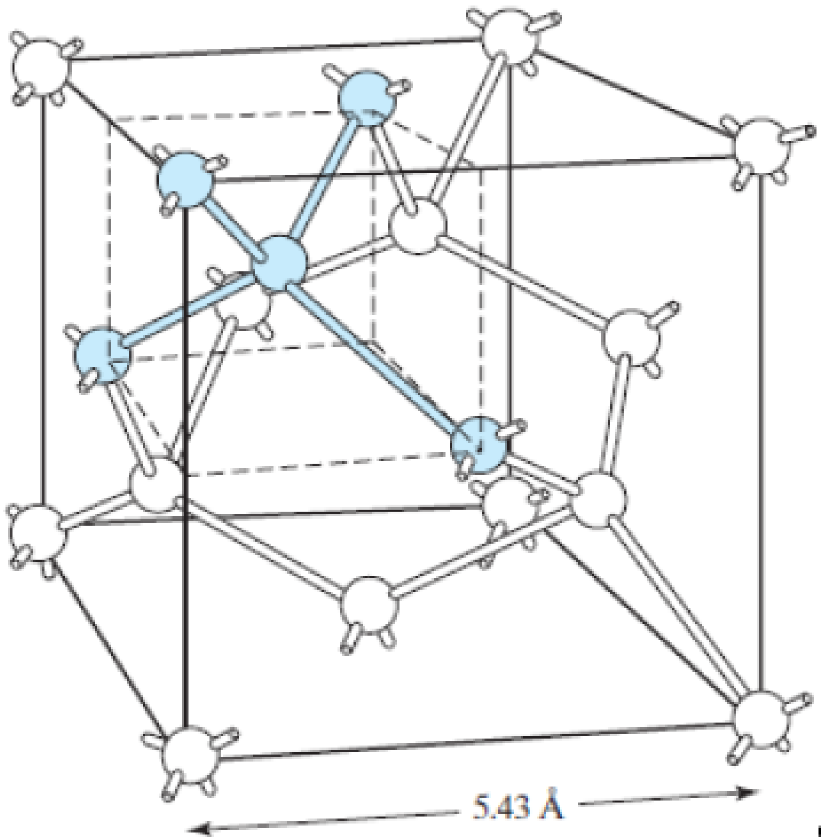
Silicon is used for integrated circuits (ICs) because its properties as a semiconductor, such as

- a stable, optimal bandgap and excellent thermal stability, allow for reliable and complex electronic components.
- Its mechanical strength, abundance and cost-effectiveness make it ideal for mass production and integration into a wide range of electronic devices.

Silicon Semiconductor

Silicon Crystal Structure

- ***Unit cell*** of silicon crystal is cubic.
- ***Each Si atom has 4 nearest neighbors.***



Modern Semiconductor Devices for Integrated Circuits (C. Hu)

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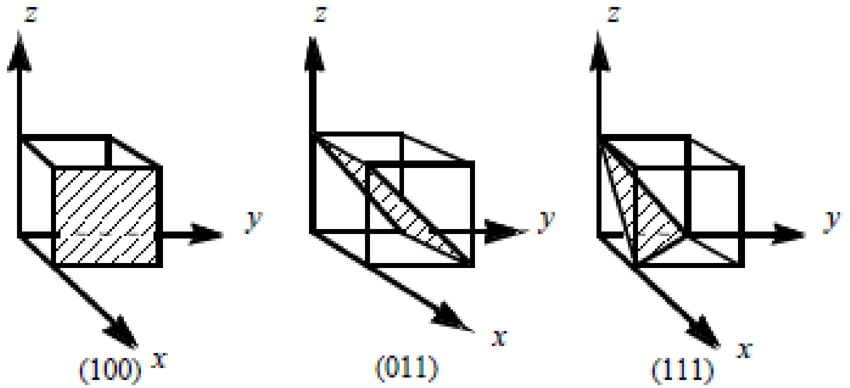
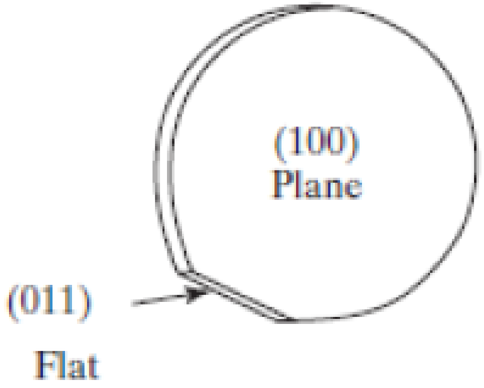
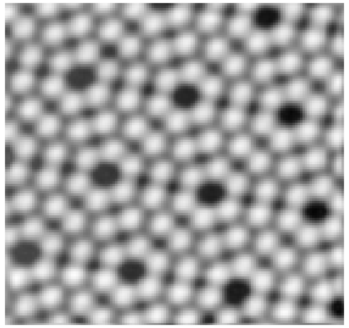
Silicon Semiconductor and crystal planes





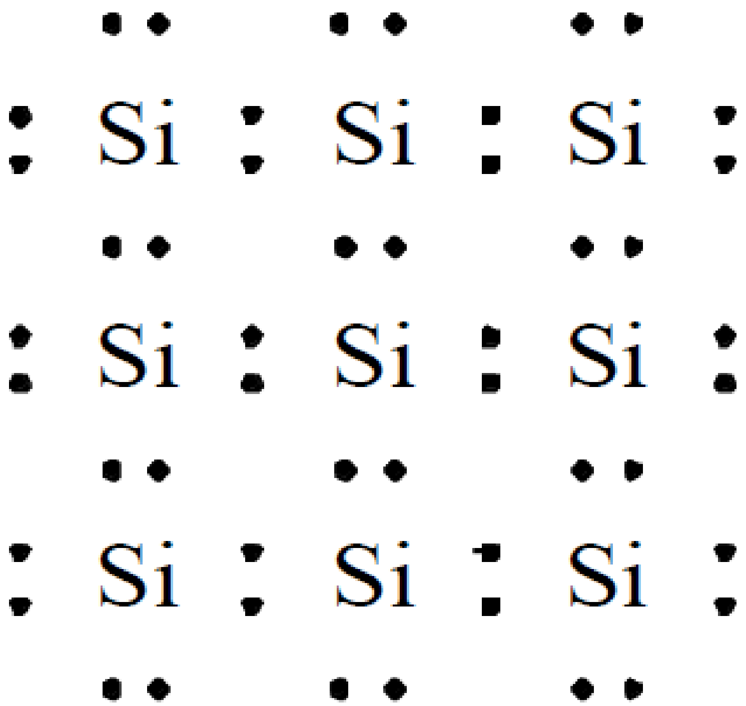


Si (111) plane

- The standard notation for crystal planes is based on the cubic unit cell.
- Silicon wafers are usually cut along the (100) plane with a flat or notch to help orient the wafer during IC fabrication.

Modern Semiconductor Devices for Integrated Circuits (C. Hu)

Silicon Semiconductor

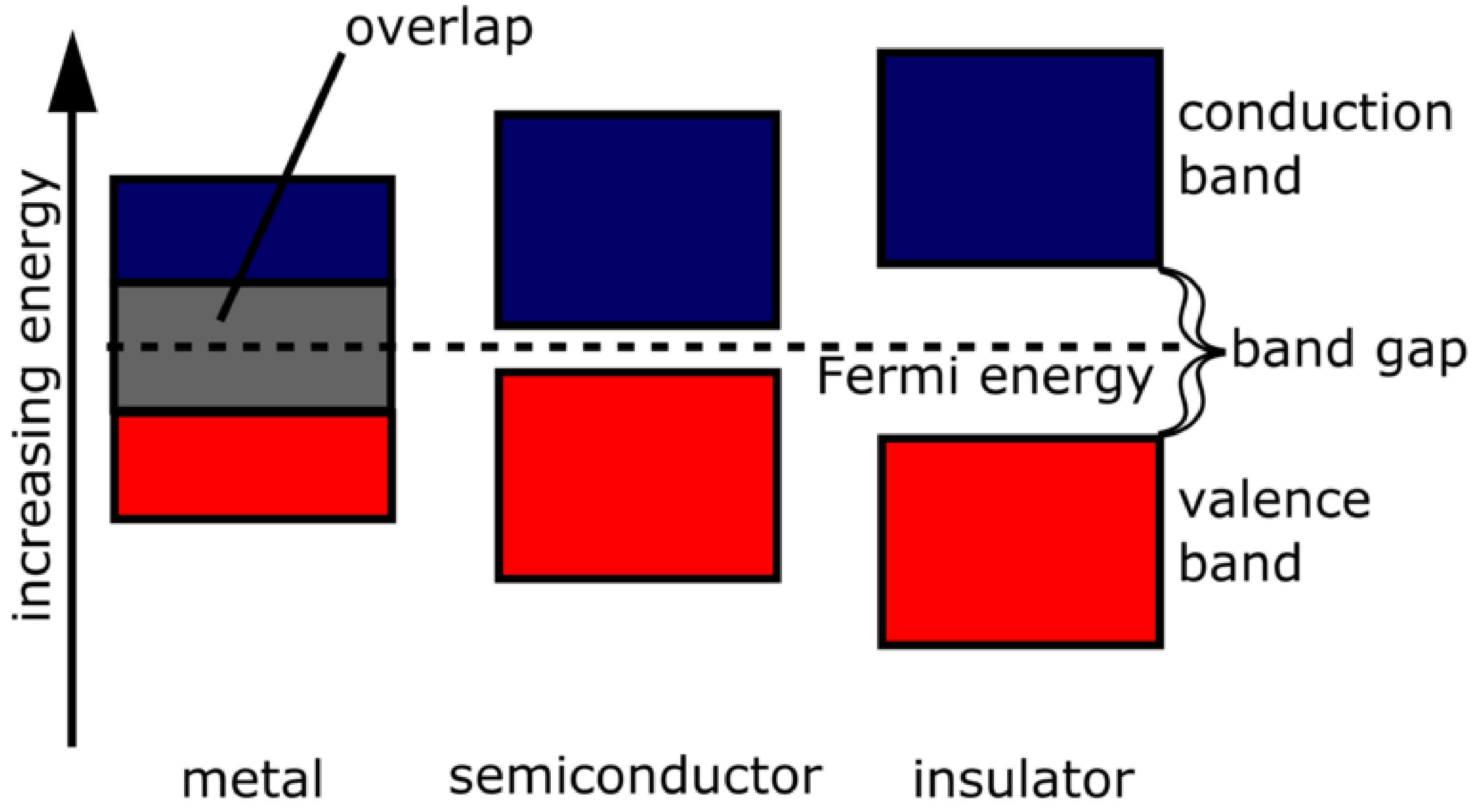


Modern Semiconductor Devices for Integrated Circuits (C. Hu)

- Silicon crystal in a two-dimensional representation.

- 4 valence electroncs

Review of Semiconductors



Ref: https://energyeducation.ca/encyclopedia/Band_gap#cite_note-3