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CATHOLIC UNIVERSITY**



**SEMMELWEIS
UNIVERSITY**



Development of Complex Curricula for Molecular Bionics and Infobionics Programs within a consortial* framework**

Consortium leader

PETER PAZMANY CATHOLIC UNIVERSITY

Consortium members

SEMMELWEIS UNIVERSITY, DIALOG CAMPUS PUBLISHER

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**Molekuláris bionika és Infobionika Szakok tananyagának komplex fejlesztése konzorciumi keretben

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TÁMOP – 4.1.2-08/2/A/KMR-2009-0006



VLSI Design Methodologies

(VLSI tervezési módszerek)

Introduction to Manufacturing of Integrated Circuits

(Bevezetés a Integrált Áramkörök Gyártásába)

PÉTER FÖLDESZ

This course gives an introduction to integrated circuits.

Starting from its raw materials, manufacturing process through the low level design issues up to the system level concerns.

The key competences of this course are the wide view of this complex technology, economical aspects, practical experiences of the advanced CAD tools.

The topics of this course:

- Trends in IC design
- Manufacturing process
- Building blocks of Integrated Circuits
- Connection between designed and manufactured structures
- Digital and analog design flows
- Low-power design
- Image, MEMS sensors and their design
- 3D integration technologies, why and how

The topics are covered in this chapter:

- Overview of IC design
- Technology roadmap and trends
 - Motivations behind and consequences
- Basic materials, methods and measures
- Manufacturing process and relation to design methods and CAD tools

Section I

The wide overview of integrated circuit design and manufacturing

Integrated circuit designs are classified as:

- Analog
 - Small transistor count precision circuits such as Data converters, Sensors etc.
- *Application Specific Integrated Circuits - ASICs*
 - These are IC's that are created for specific purposes. The most common application area for this is DSP - signal filters, image compression.
- SoC or Systems on a chip:
 - These are highly complex circuits. A network processor chip or a wireless radio chip is an example of an SoC.

How the ICs are designed?

- At low level, basically using polygon drawing tools to draw each mask. Polygons are translated to photolithography driven manufacturing steps.
- At higher level, automated CAD tools synthesizes the textual hardware description to cell and IP block seas.
- At the top, only hard IPs are wired together, and mostly software engineering remains.

While digital design is highly automated – but not a trivial task, small portion of analog design covered by automated tools.

There is no generic analog description language, as behavioral models cannot capture the complexity of the effects of parasitic on the analog behavior of the circuit.

For more complex analog chips such as data converters, the design is done at a transistor level, building up to a module level, then a block level and then integrated at a chip level. Analog design remains a difficult art.

Overview of manufacturing costs, methods

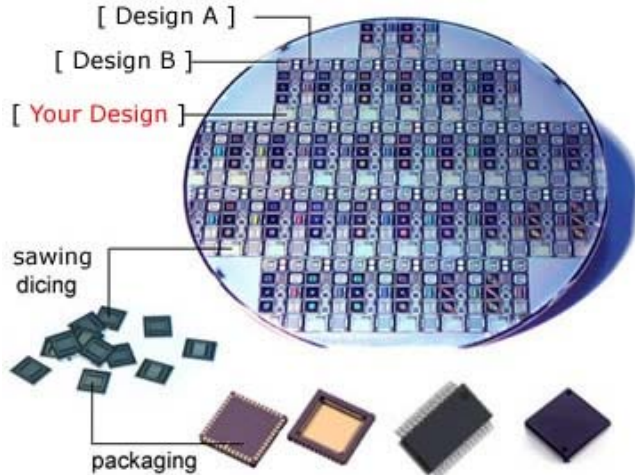
- Worth to create dedicated integrated circuit if
 - Unique physical role (sensor, shape for neuroprobe)
 - >100k pieces are needed
 - Learning curve
- Costs, just manufacturing
 - Above 180 nm node, ~50-100k\$
 - Below 45 nm node, million \$ for mask generation only

Overview of manufacturing costs, methods

- Cost sharing for prototyping: multi-project wafers
- In order to make the technology better, the complexity and cost rises exponentially. So, less and less fabs are in the worlds
 - ~1 um CMOS worked in Hungary and now advanced MEMS laboratory operates in MTA-MFA
- The common IC manufacturing is done far from the factories. These design companies are called *Fabless Design House*.

MPW offering agencies:

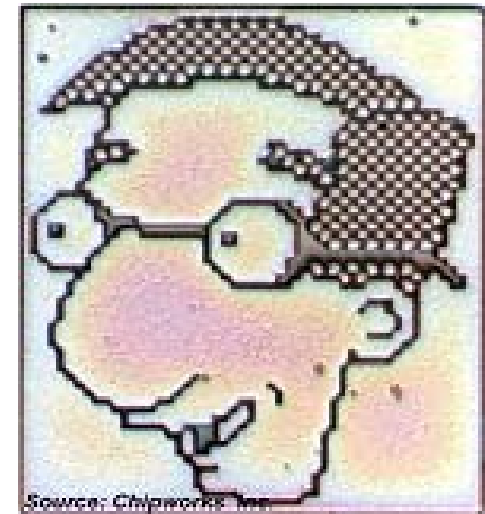
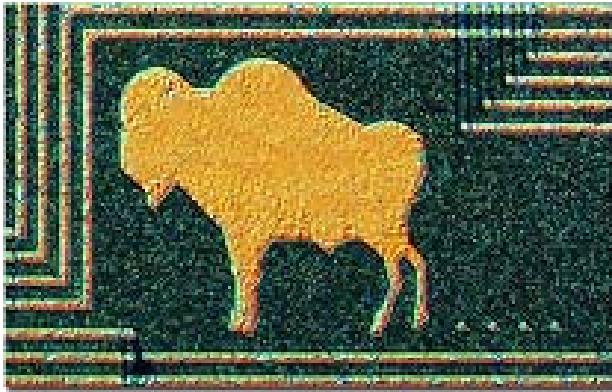
<i>Name</i>	<i>Region, funding</i>
Europractice	Belgium, partially supported, largest
MOSIS	USA, not supported, self-cost
CMP	France, but, accessible in EU
CIC	Taiwan, fully paid, but for the country
VCEC	Japan
IDEC	Korea
ICC	China
CMC	Canada
FUMEC	Mexico



Europractice flyer

Silicon can handle “art” as well (look for silicon zoo)

- In the area of hand crafted layouts, the art has been a common fun for designers
- Nowadays, the CAD tools does not allow too much special structures, they easily spot the art figures as errors, simply because they do not part of the circuitry.
(and the worker is not paid for it).



Source: Chipworks.com
<http://chipworks.com>

Section II

Technology roadmap, scaling down and trends

Aspects of scaling

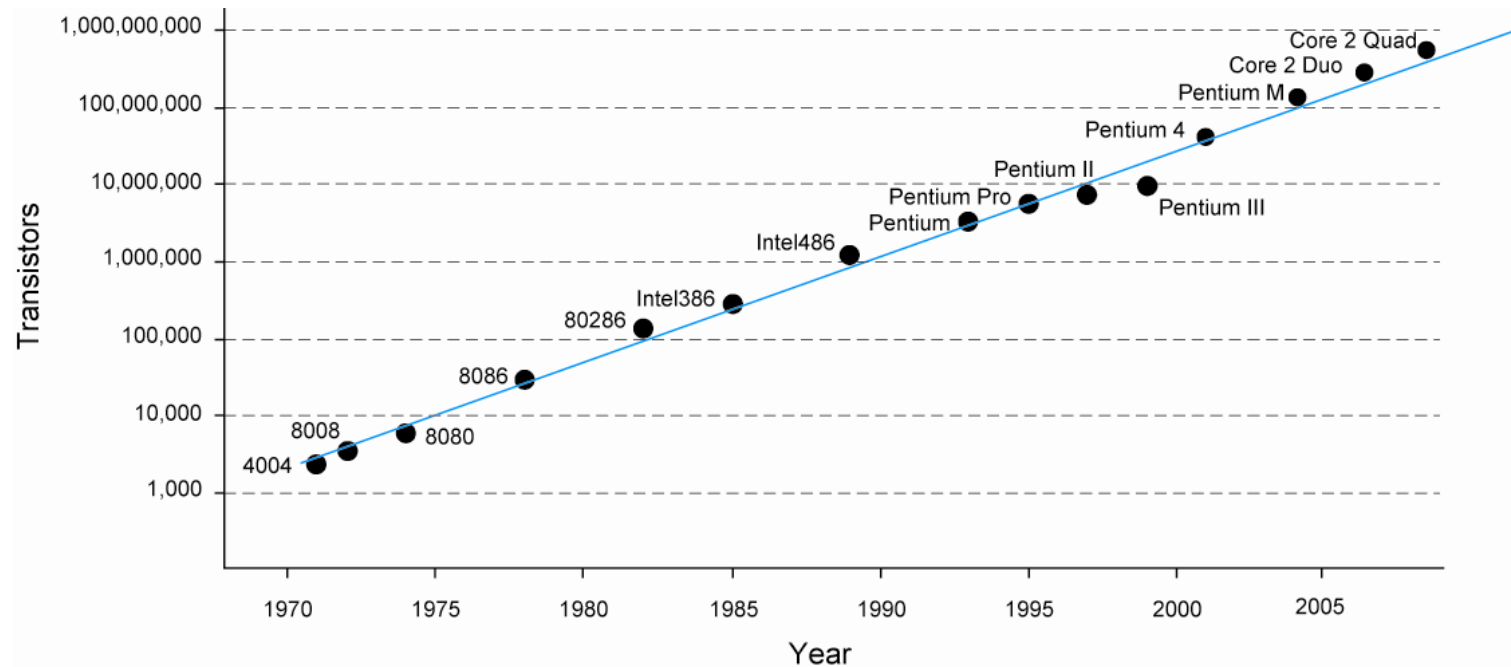
- Classic Scaling, just smaller (“More Moore”)
- Functional Diversification (“More than Moore”)
 - Integrated heterogeneous systems
- “Beyond CMOS” emerging research devices and materials, like
 - carbon-based nano-electronics, spin-based devices, ferromagnetic logic, atomic switches, and nano-electro-mechanical-system (NEMS) switches.

Scaling down (“More Moore”)

- Geometrical (constant field) Scaling—refers to the continued shrinking of horizontal and vertical physical feature sizes
- Non-geometrical process techniques and new materials that affect the electrical performance of the chip
- Design Equivalent Scaling
 - design-for-variability; low power design (sleep modes, hibernation, clock gating, multi-V_{dd}, etc.); heterogeneous multi-core SOC architectures

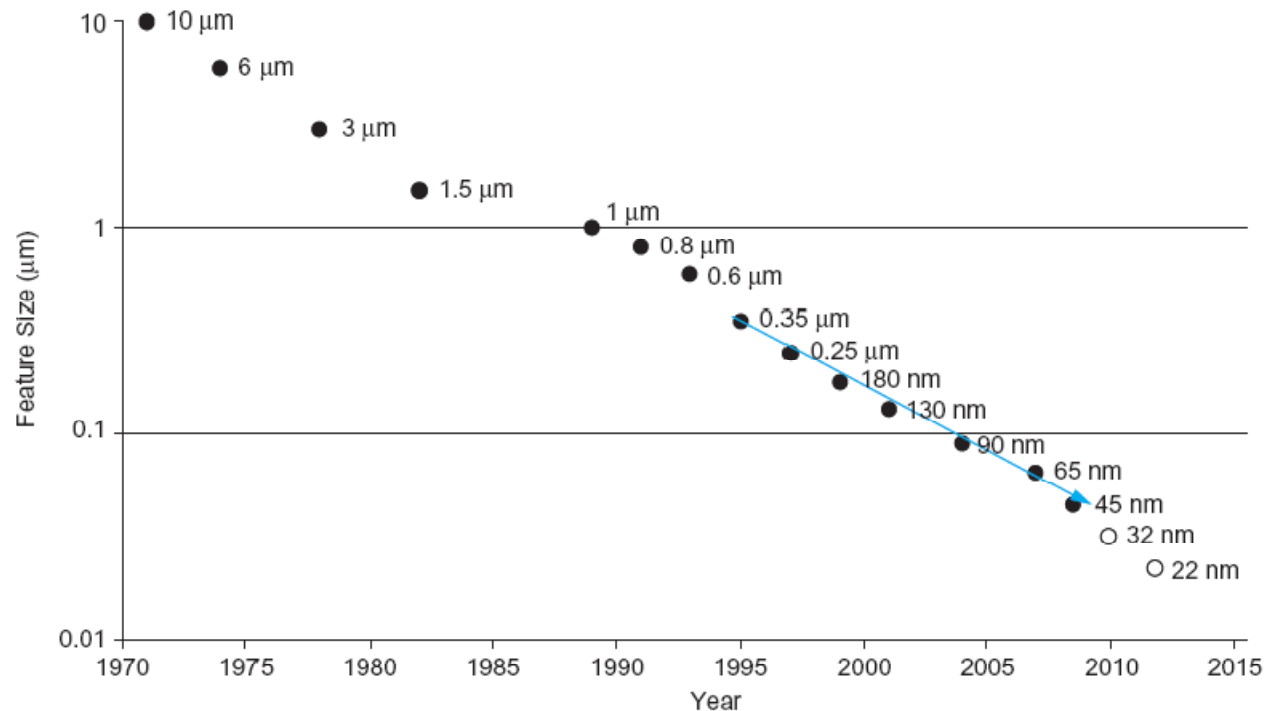
Scaling (“More Moore”)

- Gordon Moore has identified in 1965 a trend of transistor counts (doubled every 26 months)



<http://www.itrs.net/Links/2009ITRS/>

- This trend is allowed by the smaller and smaller device and metalization size. When a design became larger than ~ 1 cm² (yield, packaging, productability limit) the next node came.



<http://www.itrs.net/Links/2009ITRS>

Functional Diversification (“More than Moore”)

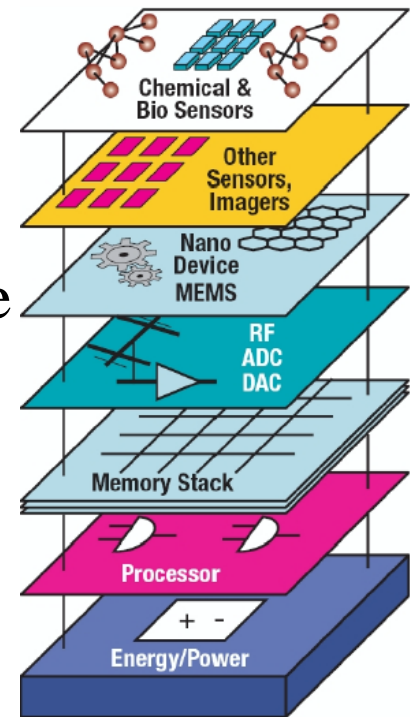
- Systems providing additional value to the end customer in different ways, e.g. non-digital functionalities like:
 - RF communication, power control, passive components, sensors, actuators
 - Migrating from the system board-level (PCB) into a particular package-level (SiP) or chip-level (SoC) solution.
- Novel technologies of 3D integration instead of planar

Application area specific technologies

- DRAM
- MPU/ASIC
 - Logic, analog, RF for wireless communication
 - High-voltage for display driver, LCD, OLED, MEMs driver
- Flash
 - NAND, NOR flash memories
- Various sensors (optical and other)
 - CCD and CMOS photosensors
 - Biochips, chemical detectors, actuators (CMOS+MEMS)

Advent of the 3D integration

- Limiting factor is the connection distance and technology incompatibility
- So, the motivation to go 3D is basically threefold:
 - Reach higher integration, higher performance
 - Integrate non compatible technologies like different semiconductor technologies
 - 3D integration would allow multicore processors and other high connectivity architectures to adopt topographic interconnection topologies



Methods of the 3D integration

- Monolithic – Electronic components and their connections (wiring) are built in layers on a single semiconductor wafer.
- Wafer-on-Wafer – Two or more semiconductor wafers are aligned, bonded, and diced into 3D ICs.
Vertical connections are either built into the wafers before bonding or else created in the stack after bonding. The via are called through-silicon via (TSV).
- Die-on-Wafer or Die-on-Die – A wafer is diced and piece-by-piece integrated on top of a complete wafer. The connection is may be wire bonding or flip chip.

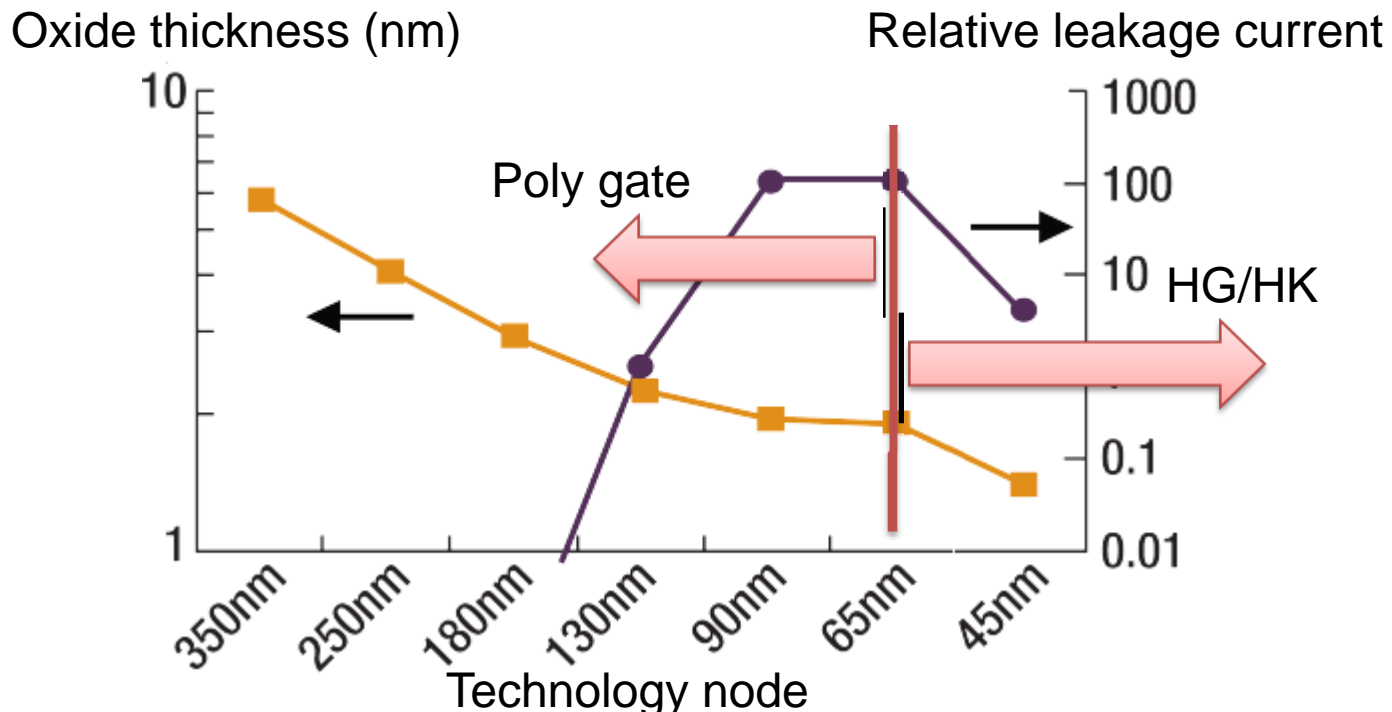
Consequences of size reduction (“scaling down”)

- Behavioral changes
 - Electrical behavior differs from classical models
 - Large leakage current, need for power management
- Technological
 - *Lithography* becomes non-trivial well below the wavelength (e.g. 193 nm UV light for 22 nm lines).
 - Application area specific technologies and materials
 - Usage of exotic materials
 - Cost of fabrication facilities increases
 - Complex gates are groups of atoms, not transistors

Electrical, behavioral changes

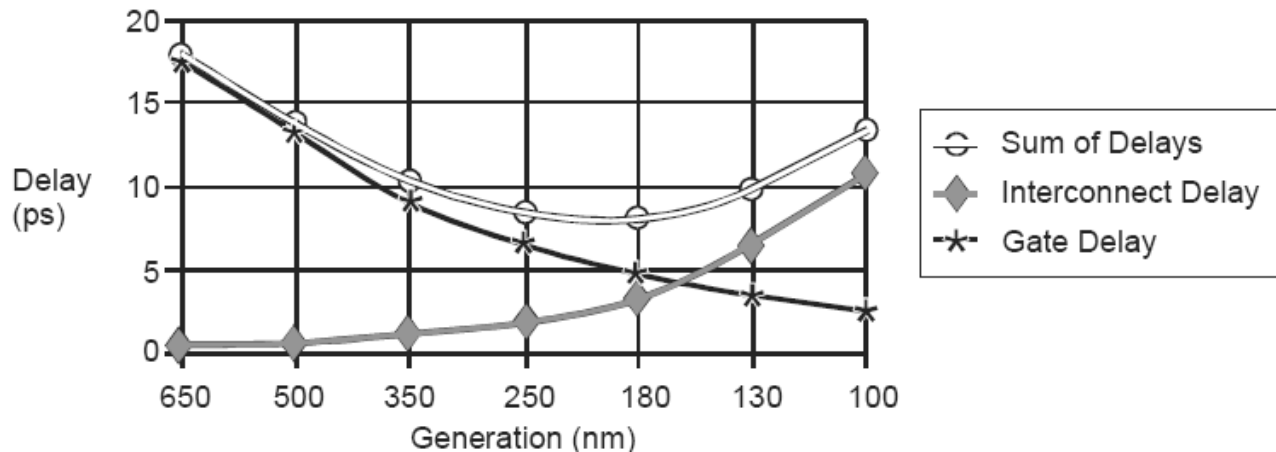
- Off state switches do not mean no current
 - High leakage current, both in channel and through gate oxide tunneling
 - Solution is thick gate oxide, “high-K” to replace SiO₂ as the gate dielectric (at 90 nm node, the gate oxide is 1.2 nm – four atoms).
 - New oxide required new gate material instead of poly-Si
- Low voltage operation, no room for analog design
 - Power supply is in the range of 1V.

- To mitigate high leakage current, migrating from Poly/SiON to metal gate/high-k (MG/HK) enabled the resumption of electrical oxide thickness scaling, while reducing gate leakage.



Electrical, behavioral changes

- Gate delay becomes smaller than wire delay
- Transistors continue to improve at smaller scales. The performance improvement gained in transistor scaling is insignificant compared to the degradation effects of interconnect scaling.



Section III

Materials and complexity measures

Overview of used raw materials.

- Substrate materials:
 - Semiconductors, because their conductivity, electrical properties can be locally controlled.
 - Silicon as material for wide-spread consumer electronics, in form of Silicon on Insulator (SOI) for high speed logic circuits, like processors.
 - Exotic materials, like GaAs for high frequency RF technologies, receivers, transmitters.
 - GaAlAs, InP, Mn doping for LEDs, solar cells

- Metals for electrical interconnection:
 - Aluminium, Copper for wiring
 - Tungsten for vias between wires
 - Gold for connecting integrated circuits to package
 - Hafnium, Rubidium, Tallium as metal gate of transistors
 - Indium for connecting integrated circuits to boards in flip-chip packages

- Other various materials:
 - Dopants to modify semiconductors (Phosphorus, Boron)
 - Silicon oxide, silicon nitrides for separation of conducting layers, wires, gates, substrate from each other.
 - Helper materials for aligning and matching crystal structure, like Titan.
 - Process materials, like Fluor as HF for semiconductor etching

Here we can see the materials involved in IC manufacturing as the time elapses in the periodic table.

1																2																																
II Helium 4.003																He Helium 4.003																																
3		4														5		6		7		8		9		10																						
Li Lithium 6.941		Be Beryllium 9.012182														B Boron 10.811		C Carbon 12.0107		N Nitrogen 14.00643		O Oxygen 15.9994		F Fluorine 18.9984032		Ne Neon 20.1797																						
11		12														13		14		15		16		17		18																						
Na Sodium 22.989770		Mg Magnesium 24.3050														Al Aluminium 26.9815385		Si Silicon 28.0855		P Phosphorus 30.973761		S Sulfur 32.066		Cl Chlorine 35.4527		Ar Argon 39.948																						
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54													
K Potassium 39.0983	Ca Calcium 40.078	Sc Scandium 44.955910	Ti Titanium 47.867	V Vanadium 50.9415	Cr Chromium 51.9961	Mn Manganese 54.938049	Fe Iron 55.845	Co Cobalt 58.933200	Ni Nickel 58.6934	Cu Copper 63.546	Zn Zinc 65.39	Ga Gallium 69.723	Ge Germanium 72.61	As Arsenic 74.92160	Se Selenium 78.96	Br Bromine 79.904	Kr Krypton 83.80	Rb Rubidium 85.4678	Sr Strontium 87.62	Y Yttrium 88.90585	Zr Zirconium 91.224	Nb Niobium 92.90638	Mo Molybdenum 95.94	Tc Technetium (98)	Ru Ruthenium 101.07	Rh Rhodium 102.90550	Pd Palladium 106.42	Ag Silver 107.8682	Cd Cadmium 112.411	In Indium 114.818	Sn Tin 118.710	Sb Antimony 121.760	Te Tellurium 127.60	I Iodine 126.90447	Xe Xenon 131.29													
55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Cs Cesium 132.90545	Ba Barium 137.327	La Lanthanum 138.9055	Hf Hafnium 178.49	Ta Tantalum 180.94788	W Tungsten 183.84	Re Rhenium 186.207	Os Osmium 190.23	Ir Iridium 192.222	Pt Platinum 195.078	Au Gold 196.96655	Hg Mercury 200.59	Tl Thallium 204.3833	Pb Lead 207.2	Bi Bismuth 208.98038	Po Polonium (209)	At Astatine (210)	Rn Radon (222)	Fr Francium (223)	Ra Radium (226)	Ac Actinium (227)	Rf Rutherfordium (261)	Db Dubnium (262)	Sg Seaborgium (263)	Bh Bohrium (264)	Hs Hassium (265)	Mt Meitnerium (266)	Lr Lawrencium (267)	Rf Rutherfordium (267)	Db Dubnium (268)	Sg Seaborgium (269)	Bh Bohrium (270)	Hs Hassium (271)	Mt Meitnerium (272)	Lr Lawrencium (273)	Rf Rutherfordium (274)	Db Dubnium (275)	Sg Seaborgium (276)	Bh Bohrium (277)	Hs Hassium (278)	Mt Meitnerium (279)	Lr Lawrencium (280)	Rf Rutherfordium (281)	Db Dubnium (282)	Sg Seaborgium (283)	Bh Bohrium (284)	Hs Hassium (285)	Mt Meitnerium (286)	Lr Lawrencium (287)
58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103			
Ce Cerium 140.116	Pr Praseodymium 140.90768	Nd Neodymium 144.24	Pm Promethium (145)	Sm Samarium 150.36	Eu Europium 151.964	Gd Gadolinium 157.25	Tb Terbium 158.92534	Dy Dysprosium 162.50	Ho Holmium 164.93032	Er Erbium 167.26	Tm Thulium 168.93421	Yb Ytterbium 173.04	Lu Lutetium 174.967	Th Thorium 232.0375	Pa Protactinium 231.036888	U Uranium 238.0289	Np Neptunium (237)	Pu Plutonium (242)	Am Americium (243)	Cm Curium (247)	Bk Berkelium (247)	Cf Californium (251)	Es Einsteinium (252)	Fm Fermium (257)	Md Mendelevium (258)	No Nobelium (259)	Lr Lawrencium (262)	Rf Rutherfordium (261)	Db Dubnium (262)	Sg Seaborgium (263)	Bh Bohrium (264)	Hs Hassium (265)	Mt Meitnerium (266)	Lr Lawrencium (267)	Rf Rutherfordium (268)	Db Dubnium (269)	Sg Seaborgium (270)	Bh Bohrium (271)	Hs Hassium (272)	Mt Meitnerium (273)	Lr Lawrencium (274)	Rf Rutherfordium (275)	Db Dubnium (276)	Sg Seaborgium (277)	Bh Bohrium (278)	Hs Hassium (279)	Mt Meitnerium (280)	Lr Lawrencium (281)

1980's

Here we can see the materials involved in IC manufacturing as the time elapses in the periodic table.

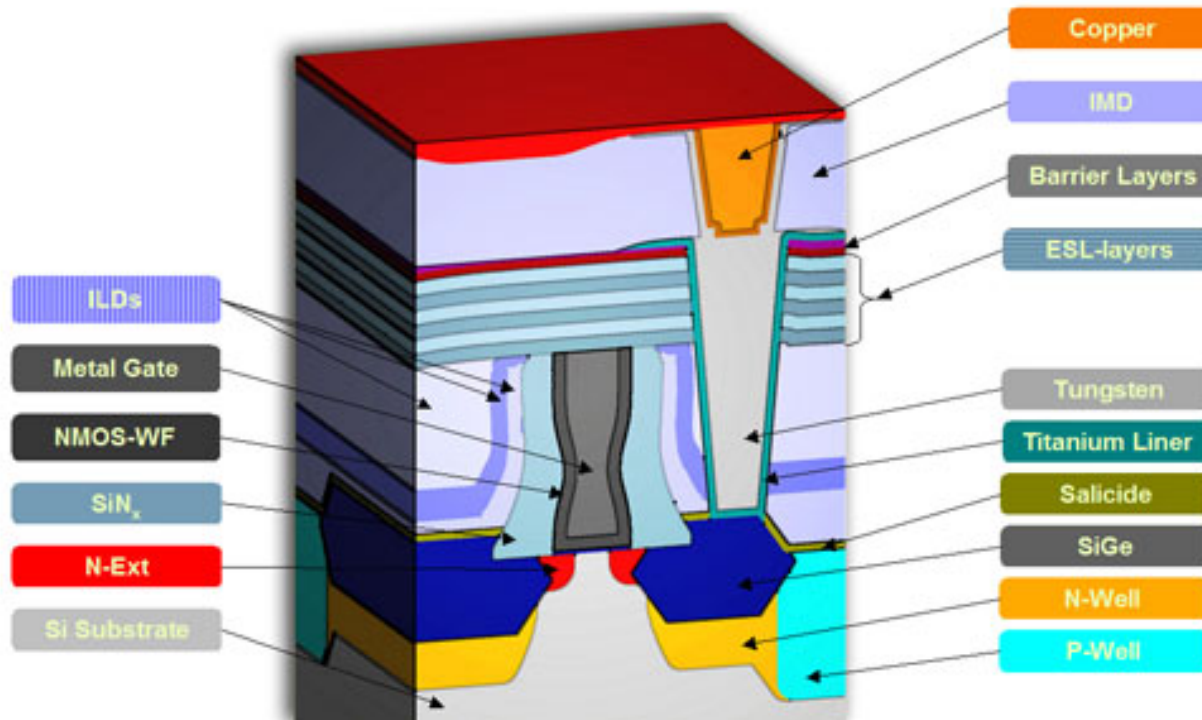
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11 Na Sodium 22.98976928		12 Mg Magnesium 24.3050		13 Al Aluminum 26.9815385		14 Si Silicon 28.0855		15 P Phosphorus 30.973761		16 S Sulfur 32.066		17 Cl Chlorine 35.4527		18 Ar Argon 39.948																					
19 K Potassium 39.0983		20 Ca Calcium 40.078		21 Sc Scandium 44.955912		22 Ti Titanium 47.867		23 V Vanadium 50.9415		24 Cr Chromium 51.9961		25 Mn Manganese 54.938045		26 Fe Iron 55.845		27 Co Cobalt 58.933200		28 Ni Nickel 58.6934		29 Cu Copper 63.546		30 Zn Zinc 65.39		31 Ga Gallium 69.723		32 Ge Germanium 72.61		33 As Arsenic 74.92160		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)		44 Ru Ruthenium 101.07		45 Rh Rhodium 102.90550		46 Pd Palladium 106.42		47 Ag Silver 107.8682		48 Cd Cadmium 112.411		49 In Indium 114.818		50 Sn Tin 118.710		51 Sb Antimony 121.760		52 Te Tellurium 127.60		53 I Iodine 126.90447		54 Xe Xenon 131.29	
55 Cs Cesium 132.90545		56 Ba Barium 137.327		57 La Lanthanum 138.9055		58 Hf Hafnium 178.49		59 Ta Tantalum 180.94788		60 W Tungsten 183.84		61 Re Rhenium 186.207		62 Os Osmium 190.23		63 Ir Iridium 192.222		64 Pt Platinum 195.078		65 Au Gold 196.96655		66 Hg Mercury 200.59		67 Tl Thallium 204.3833		68 Pb Lead 207.2		69 Bi Bismuth 208.98038		70 Po Polonium (209)		71 At Astatine (210)		72 Rn Radon (222)	
87 Fr Francium (223)		88 Ra Radium (226)		89 Ac Actinium (227)		104 Rf Rutherfordium (261)		105 Db Dubnium (262)		106 Sg Seaborgium (263)		107 Bh Bohrium (264)		108 Hs Hassium (265)		109 Mt Meitnerium (266)		(269)		(272)		(277)													
58 Ce Cerium 140.116		59 Pr Praseodymium 140.90765		60 Nd Neodymium 144.24		61 Pm Promethium (145)		62 Sm Samarium 150.36		63 Eu Europium 151.964		64 Gd Gadolinium 157.25		65 Tb Terbium 158.92534		66 Dy Dysprosium 162.50		67 Ho Holmium 164.93032		68 Er Erbium 167.255		69 Tm Thulium 168.93421		70 Yb Ytterbium 173.04		71 Lu Lutetium 174.967									
90 Th Thorium 232.0375		91 Pa Protactinium 231.03688		92 U Uranium 238.0289		93 Np Neptunium (237)		94 Pu Plutonium (244)		95 Am Americium (243)		96 Cm Curium (247)		97 Bk Berkelium (247)		98 Cf Californium (251)		99 Es Einsteinium (252)		100 Fm Fermium (257)		101 Md Mendelevium (258)		102 No Nobelium (259)		103 Lr Lawrencium (262)									

1990's

Here we can see the materials involved in IC manufacturing as the time elapses in the periodic table.

1 H Hydrogen (1.00794)																	2 He Helium (4.0026)
3 Li Lithium (6.941)	4 Be Beryllium (9.012182)											5 B Boron (10.81)	6 C Carbon (12.0107)	7 N Nitrogen (14.00654)	8 O Oxygen (15.9994)	9 F Fluorine (18.9984032)	10 Ne Neon (20.1797)
11 Na Sodium (22.9897702)	12 Mg Magnesium (24.304)											13 Al Aluminum (26.9815385)	14 Si Silicon (28.0855)	15 P Phosphorus (30.973761)	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 (44.955912)	22 Ti Titanium (47.867)	23 V Vanadium (50.9415)	24 Cr Chromium (51.9961)	25 Mn Manganese (54.938045)	26 Fe Iron (55.845)	27 Co Cobalt (58.933200)	28 Ni Nickel (58.6934)	29 Cu Copper (63.546)	30 Zn Zinc (65.38)	31 Ga Gallium (69.723)	32 Ge Germanium (72.64)	33 As Arsenic (74.9216)	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)	44 Ru Ruthenium (101.07)	45 Rh Rhodium (102.90550)	46 Pd Palladium (106.42)	47 Ag Silver (107.8682)	48 Cd Cadmium (112.411)	49 In Indium (114.818)	50 Sn Tin (118.710)	51 Sb Antimony (121.760)	52 Te Tellurium (127.60)	53 I Iodine (126.90447)	54 Xe Xenon (131.29)
55 Cs Cesium (132.90545)	56 Ba Barium (137.327)	57 La Lanthanum (138.9048)	72 Hf Hafnium (178.49)	73 Ta Tantalum (180.94788)	74 W Tungsten (183.84)	75 Re Rhenium (186.207)	76 Os Osmium (190.23)	77 Ir Iridium (192.222)	78 Pt Platinum (195.084)	79 Au Gold (196.966569)	80 Hg Mercury (200.59)	81 Tl Thallium (204.3833)	82 Pb Lead (207.2)	83 Bi Bismuth (208.9804)	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (264)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 (269)	111 (272)	112 (277)						
58 Ce Cerium (140.12)	59 Pr Praseodymium (140.90766)	60 Nd Neodymium (144.242)	61 Pm Promethium (145)	62 Sm Samarium (150.36)	63 Eu Europium (151.964)	64 Gd Gadolinium (157.25)	65 Tb Terbium (158.92532)	66 Dy Dysprosium (162.50015)	67 Ho Holmium (164.930329)	68 Er Erbium (167.2593)	69 Tm Thulium (168.93486)	70 Yb Ytterbium (173.054688)	71 Lu Lutetium (174.96706)				
90 Th Thorium (232.0377)	91 Pa Protactinium (231.036888)	92 U Uranium (238.02891)	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)				

2000's



22 nm metal gate transistor cross section. Note, that most of the materials are used to avoid diffusion of other structural blocks

Complexity measures

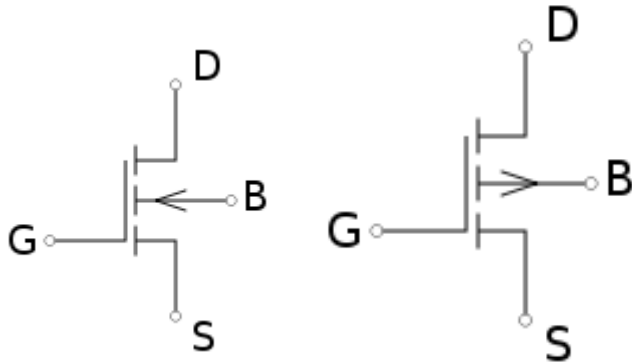
- SSI, MSI, LSI (small-, medium-, large-*scale integration*) under 100,000 transistors
- Over 100,000 transistors: VLSI (very large SI)
- More than 1 million: ULSI (ultra large SI)
- WSI (wafer-scale integration)
- SOC, system-on-a-chip, complex computers are integrated (analog front-end, memory, peripheries, processors)
- *Multi-chip-modules* and 3D technologies

What are the elements typically needed?

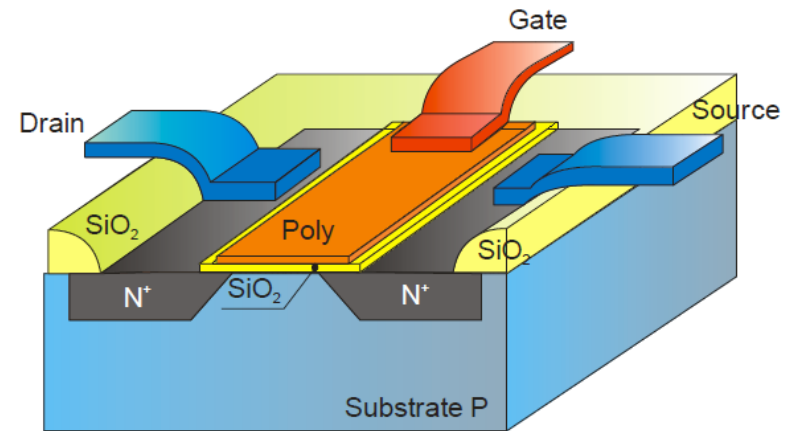
- Binary switch
- Analog controlled sources (current, voltage)
- Resistors
 - Doped diffusion, poly-Si
- Capacitors
 - Metal to metal wires, metal-insulator-metal (MIM)
 - Poly-Si to poly-Si
- Inductivity
 - Metal loops

MOS Transistor as well

MOS Transistor based elements



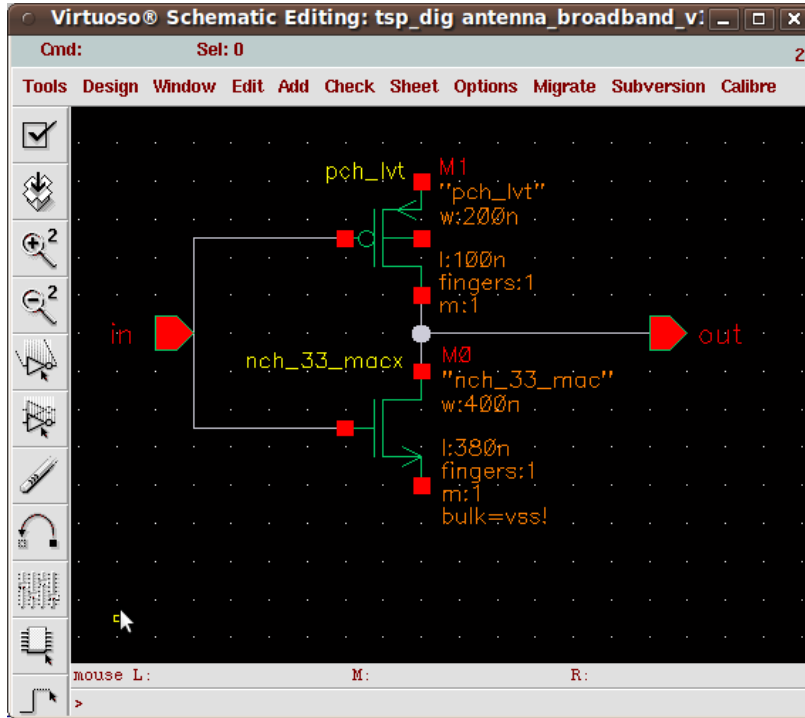
The symbol of the MOST



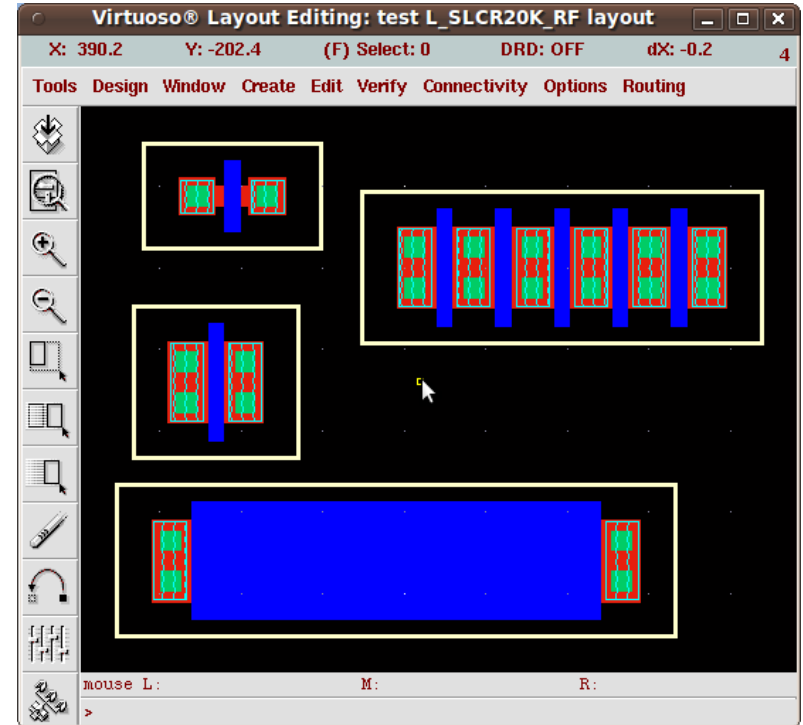
Rough cross section and bird's eye view

http://commons.wikimedia.org/wiki/File:MOSFET_Manufacture_-_7_-_metalisation.svg

MOS Transistor in the design environment

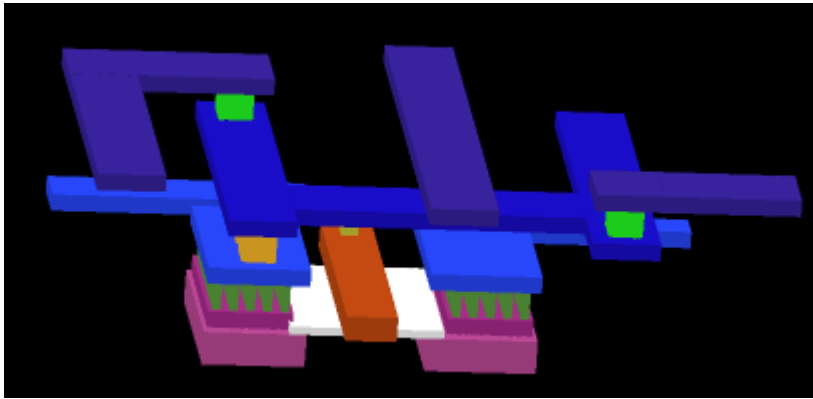


Schematic of two MOSTs

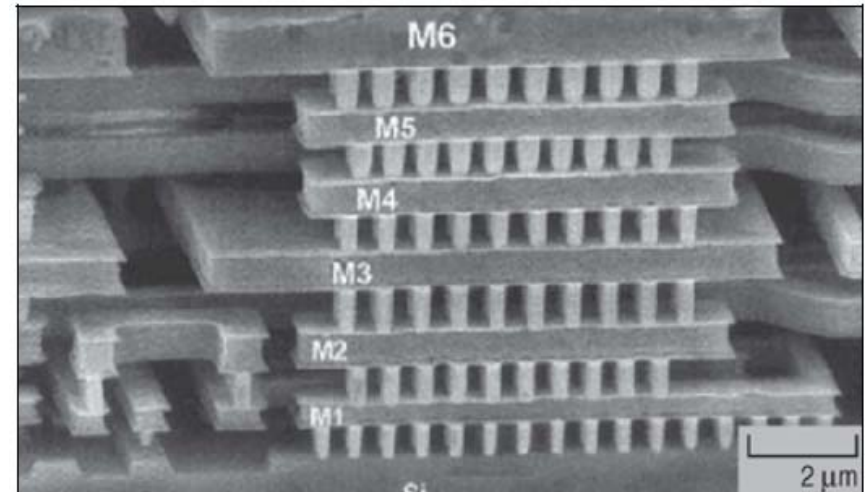


Layout of some MOSTs

Other views of the same transistors, circuits.



3D view of a MOST and its wiring

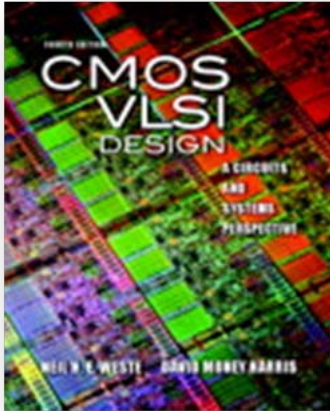


Final view of a 0.35 μm
technology with six metal layers.

Conclusions:

- We learned that the IC manufacturing is a difficult and expensive industry and business.
- There are a huge number of variants and technologies, there is no one and only method that fit all requirements.
- Fabless IC design is introduced and the design can be “anywhere”.

Recommended literature:



CMOS VLSI Design: A Circuits and Systems Perspective, 4/E
Neil Weste, *Macquarie University and The University of Adelaide*
David Harris, *Harvey Mudd College*
Publisher: Addison-Wesley

CMOS Transistor Layout KungFu ebook

Lee Eng Han et al.

www.eda-utilities.com/CMOS_Transistor_Layout_KungFu.pdf

Comprehension questions:

- I. Which kind of trends exists in the integrated circuit industry?
- II. What are motivations behind 3D integration?
- III. What are the major classes of ICs?
- IV. What does VLSI means?

