Microelectronics and Micromechanics

Peter Hadley

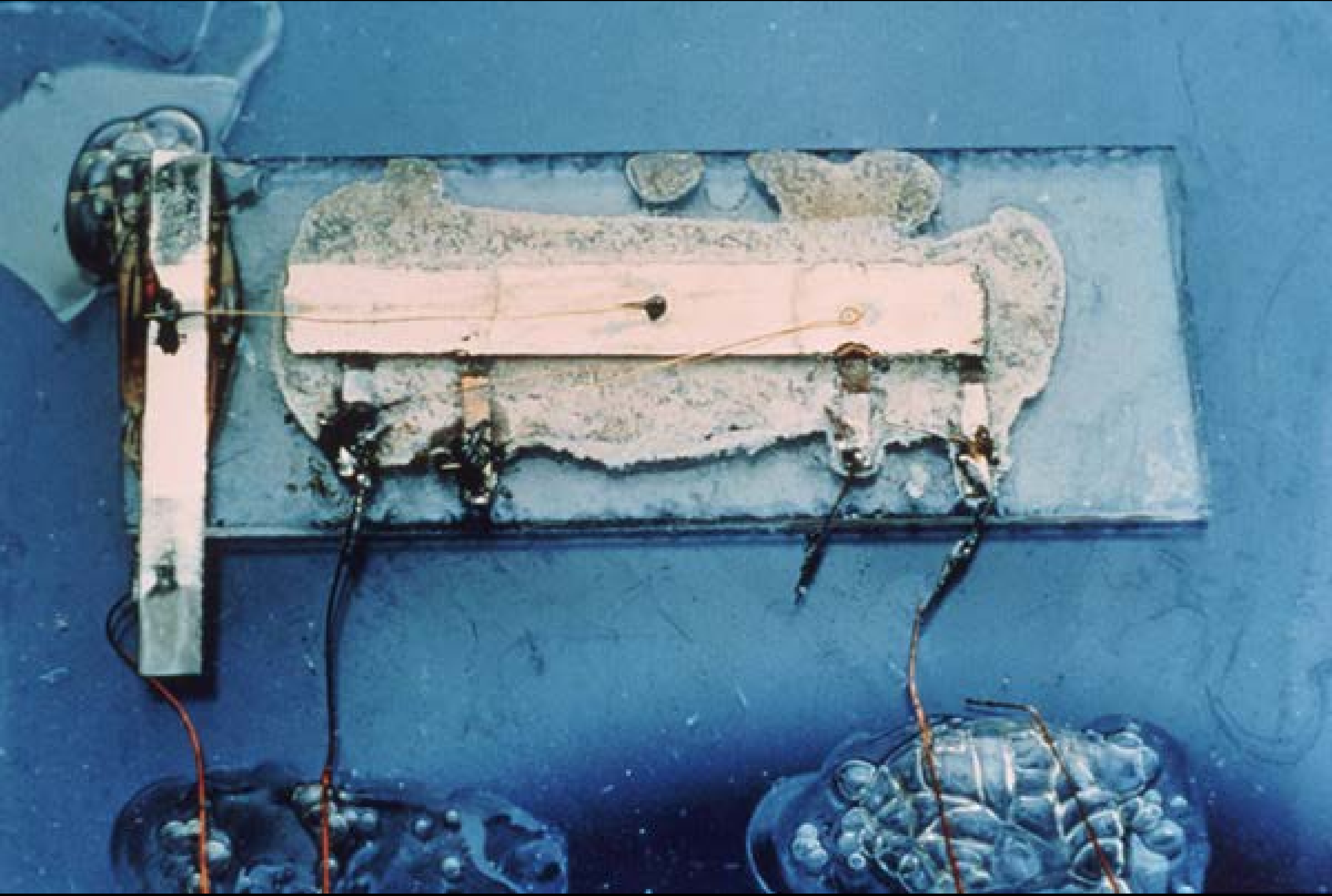
1 Mikro- und Nanotechnologien in der Mikroelektronik

1.1 Grundprozesse

Ausgangspunkt ist der Siliziumwafer (früher Ge, heute auch GaAs). Ist ein Einkristall mit sehr geringer Defektdichte und hochrein (typisch einige Defekte/cm^2). Herstellung meist nach dem Czochralskiverfahren (Ziehen aus der Schmelze).

Zur Zeit typische Waferdurchmesser 10 cm (4") bis 20 cm (8"). Länge des Einkristalls bis 2 m; Dicke der Wafer $\approx$ 0.5 mm. (Fa. Wacker Chemie/Burghausen, Bayern).

Auf dem Wafer werden in vielfacher Anzahl die IC's (integrated circuits) hergestellt (chips, dies), typische Größen: 5x6mm^2 (Logikbausteine), 4x10 mm^2 (Speicher). Pro chip mehrere Millionen Bausteine (Transistoren, Kondensatoren). Dimensionen im μm und sub-μm Bereich.



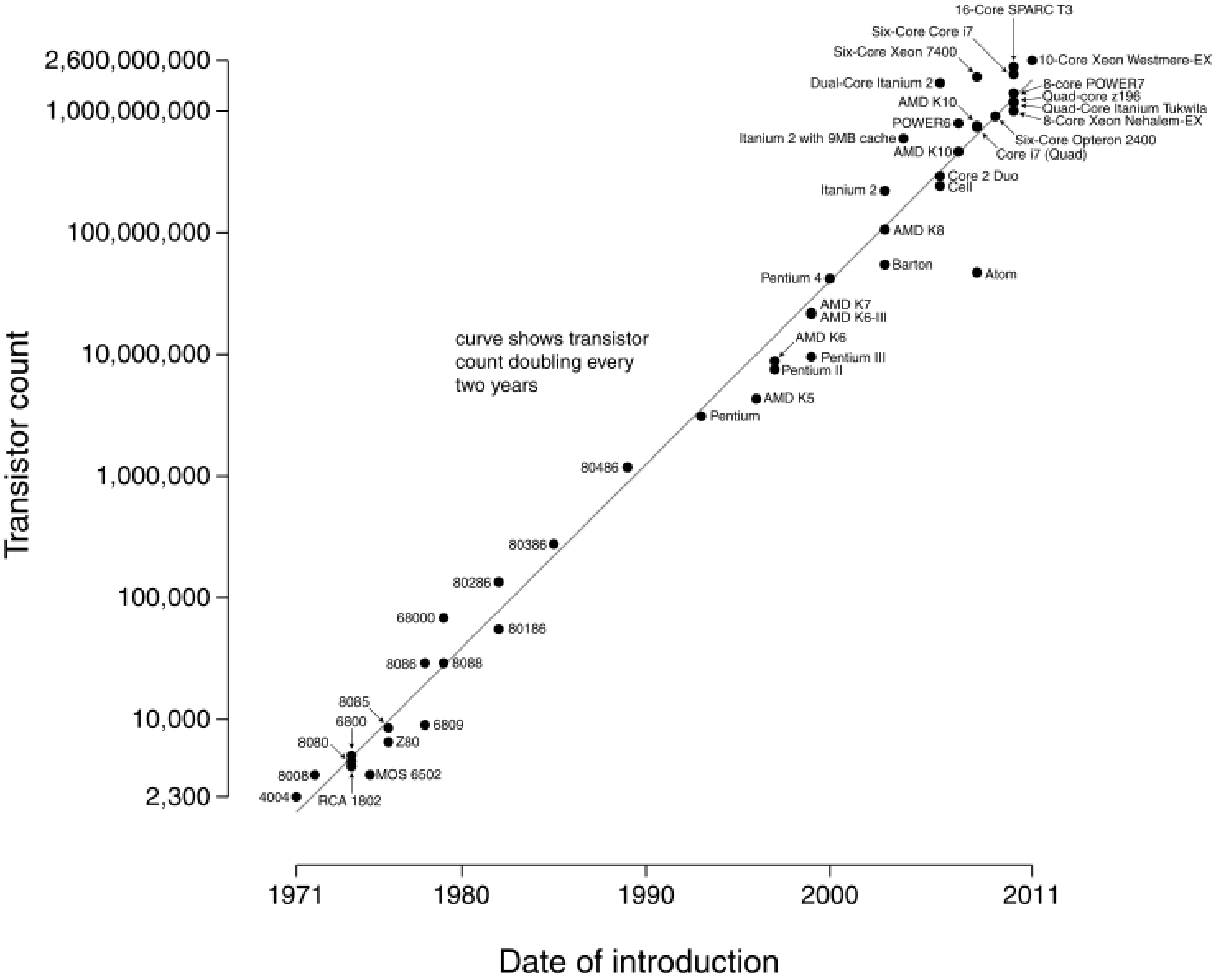
Jack Kilby's first integrated circuit 1958

Moore's law

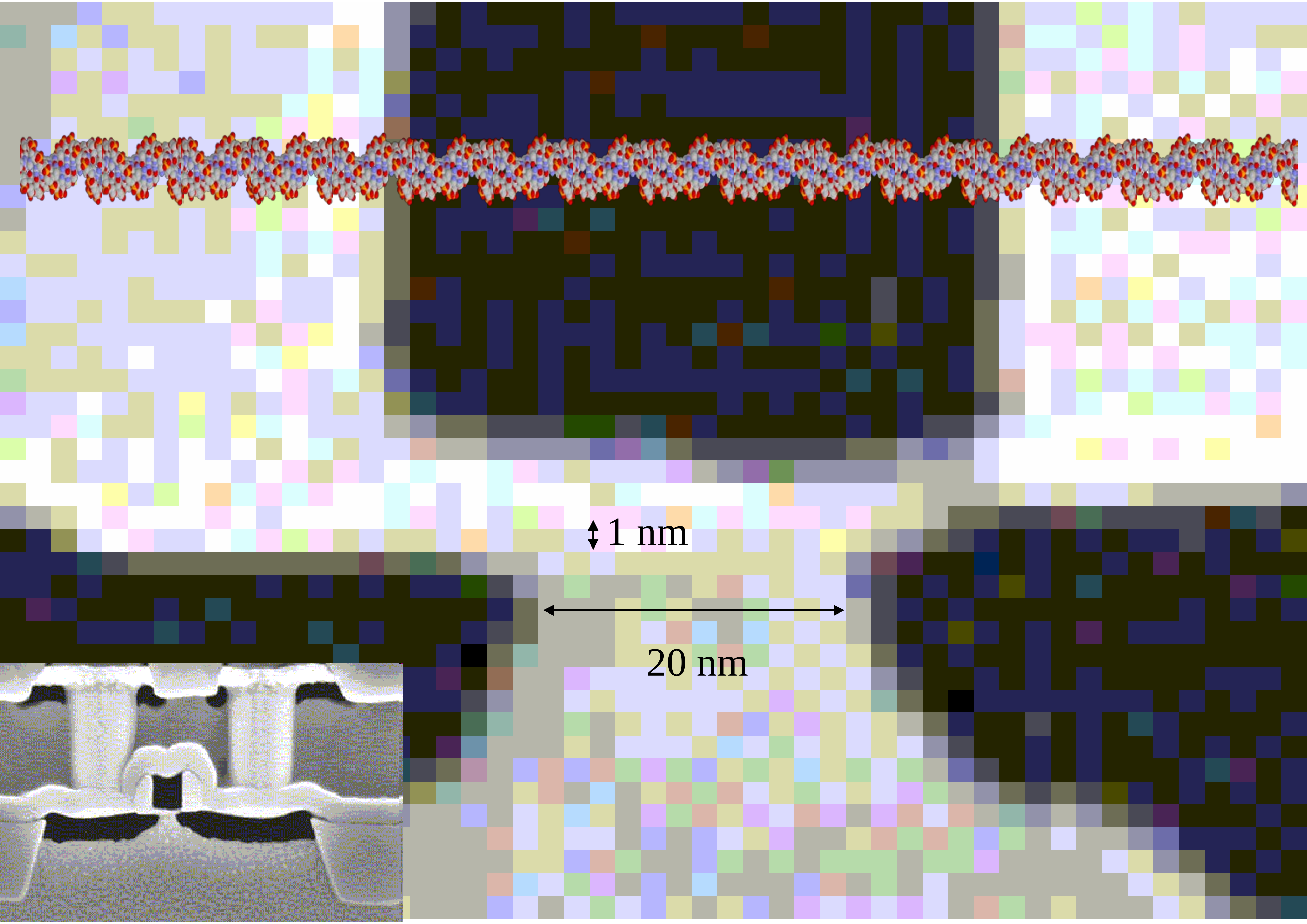
The complexity for minimum component costs has increased at a rate of *roughly a factor of two per year*. Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years.

G. Moore, 1965

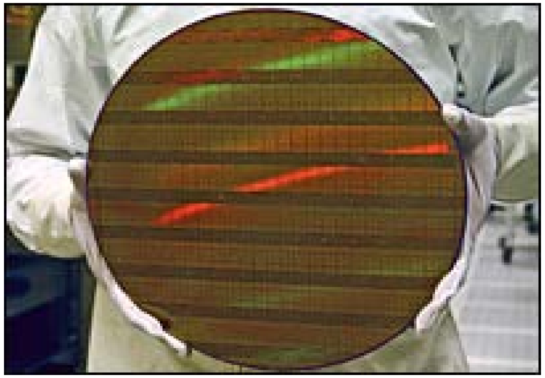
Microprocessor Transistor Counts 1971-2011 & Moore's Law



http://en.wikipedia.org/wiki/Moore%27s_law#mediaviewer/File:Transistor_Count_and_Moore%27s_Law_-_2011.svg


1 nm
20 nm

Microelectronics



Silicon chips are used in computers, mobile telephones, and microcontrollers.

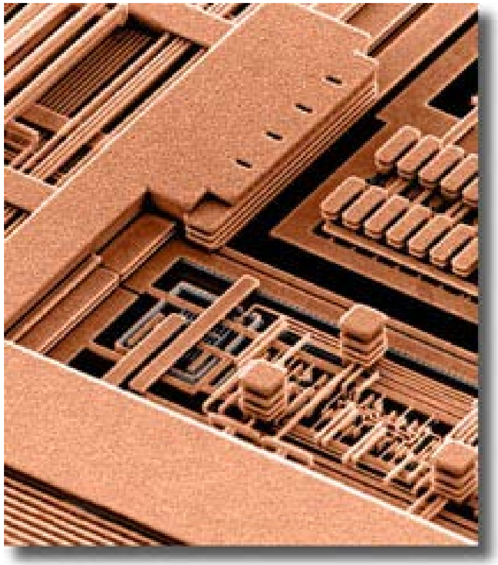
1 trillion transistors are produced simultaneously on a wafer.

Gate length ~ 15 nm

1 μprocessor ~ 1 billion transistors ~ 100 Euros
1 transistor for 10^{-5} cents.

10^5 transistors ~ 1 cent → packaging is the major cost for simple circuits

100 euro/cm^2



International Technology Roadmap for Semiconductors

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2009 ERRATA-Executive Summary, list of corrections

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International Technology Roadmap for Semiconductors

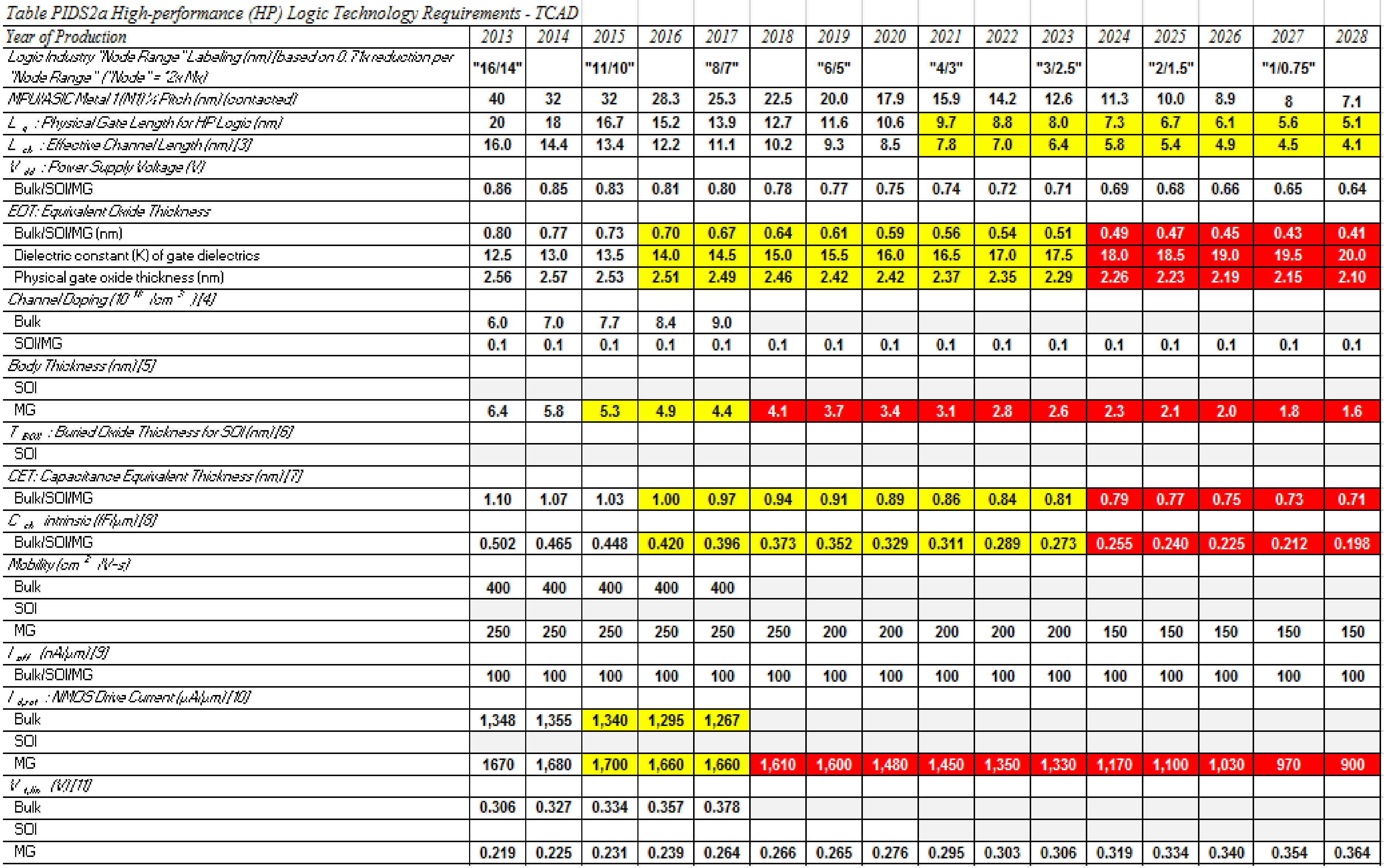

Table PIDS2a High-performance (HP) Logic Technology Requirements - TCAD																
Year of Production	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*
Logic Industry "Node Range" Labeling (nm) [based on 0.71x reduction per "Node Range" ("Node" = 2x Mx)	"16/14"		"11/10"		"8/7"		"6/5"		"4/3"		"3/2.5"		"2/1.5"		"1/0.75"	
MPU/ASIC Metal 1 (M1) ½ Pitch (nm) (contacted)	40	32	32	28.3	25.3	22.5	20.0	17.9	15.9	14.2	12.6	11.3	10.0	8.9	8	7.1
L_g : Physical Gate Length for HP Logic (nm)	20	18	16.7	15.2	13.9	12.7	11.6	10.6	9.7	8.8	8.0	7.3	6.7	6.1	5.6	5.1
L_{ch} : Effective Channel Length (nm) [3]	16.0	14.4	13.4	12.2	11.1	10.2	9.3	8.5	7.8	7.0	6.4	5.8	5.4	4.9	4.5	4.1
V_{dd} : Power Supply Voltage (V)																
Bulk/SOI/MG	0.86	0.85	0.83	0.81	0.80	0.78	0.77	0.75	0.74	0.72	0.71	0.69	0.68	0.66	0.65	0.64
EOT: Equivalent Oxide Thickness																
Bulk/SOI/MG (nm)	0.80	0.77	0.73	0.70	0.67	0.64	0.61	0.59	0.56	0.54	0.51	0.49	0.47	0.45	0.43	0.41
Dielectric constant (K) of gate dielectrics	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5	18.0	18.5	19.0	19.5	20.0
Physical gate oxide thickness (nm)	2.56	2.57	2.53	2.51	2.49	2.46	2.42	2.42	2.37	2.35	2.29	2.26	2.23	2.19	2.15	2.10
Channel Doping (10^{18} /cm^3) [4]																
Bulk	6.0	7.0	7.7	8.4	9.0											
SOI/MG	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Body Thickness (nm) [5]																
SOI																
MG	6.4	5.8	5.3	4.9	4.4	4.1	3.7	3.4	3.1	2.8	2.6	2.3	2.1	2.0	1.8	1.6
T_{BOX} : Buried Oxide Thickness for SOI (nm) [6]																
SOI																
CET: Capacitance Equivalent Thickness (nm) [7]																
Bulk/SOI/MG	1.10	1.07	1.03	1.00	0.97	0.94	0.91	0.89	0.86	0.84	0.81	0.79	0.77	0.75	0.73	0.71
C_{ch} intrinsic (fF/μm) [8]																
Bulk/SOI/MG	0.502	0.465	0.448	0.420	0.396	0.373	0.352	0.329	0.311	0.289	0.273	0.255	0.240	0.225	0.212	0.198
Mobility (cm^2 /V-s)																
Bulk	400	400	400	400	400											
SOI																
MG	250	250	250	250	250	250	200	200	200	200	200	150	150	150	150	150
I_{off} (nA/μm) [9]																
Bulk/SOI/MG	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
$I_{d,sat}$: NMOS Drive Current (μA/μm) [10]																
Bulk	1,348	1,355	1,340	1,295	1,267											
SOI																
MG	1670	1,680	1,700	1,660	1,660	1,610	1,600	1,480	1,450	1,350	1,330	1,170	1,100	1,030	970	900
$V_{t,lin}$ (V) [11]																
Bulk	0.306	0.327	0.334	0.357	0.378											
SOI																
MG	0.219	0.225	0.231	0.239	0.264	0.266	0.265	0.276	0.295	0.303	0.306	0.319	0.334	0.340	0.354	0.364

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Micromechanics

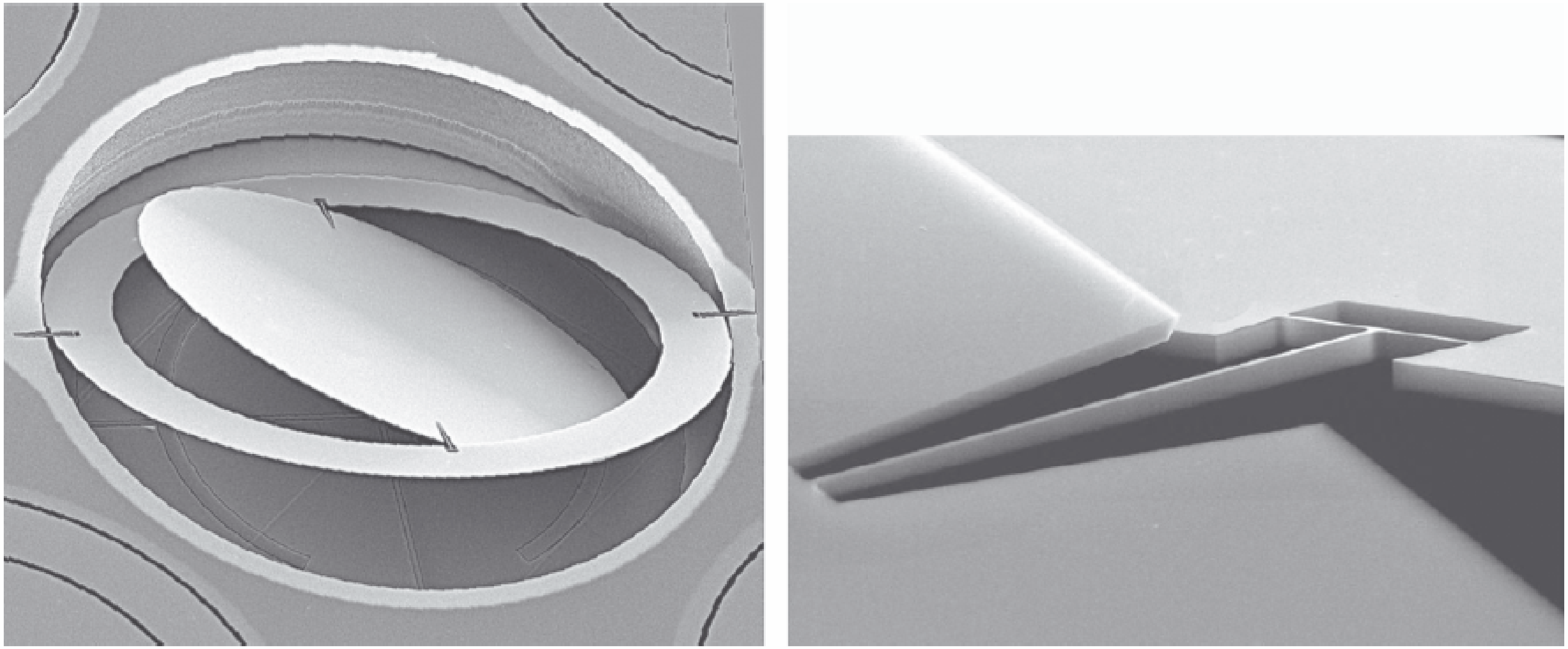
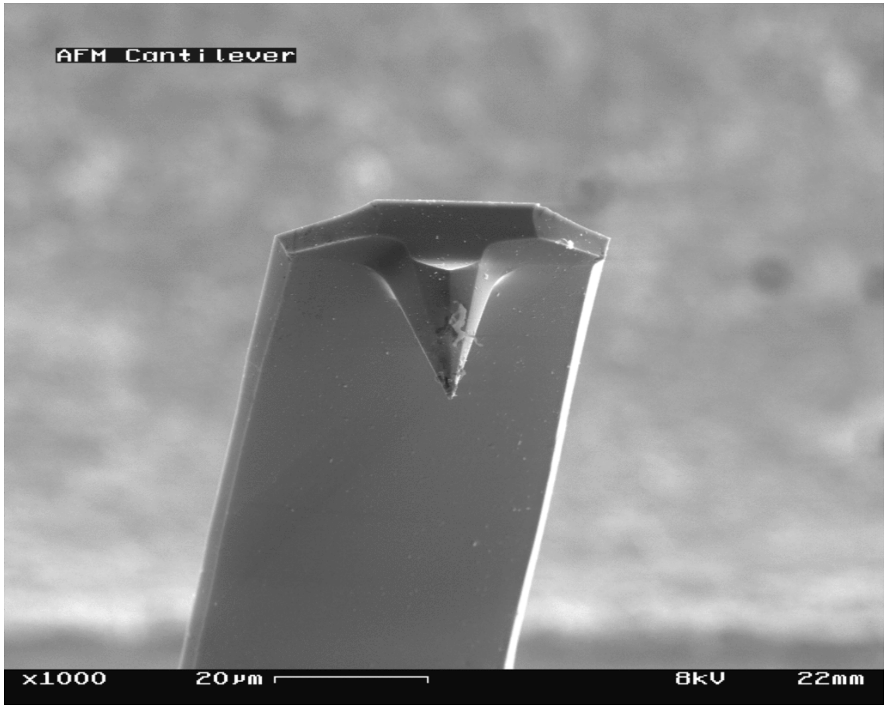


Figure 1.2 Micromirror made of silicon, 1 mm in diameter, is supported by torsion bars 1.2 µm wide and 4 µm thick (detail figure). Reproduced from Greywall *et al.* (2003), Copyright 2003, by permission of IEEE

Micromechanics



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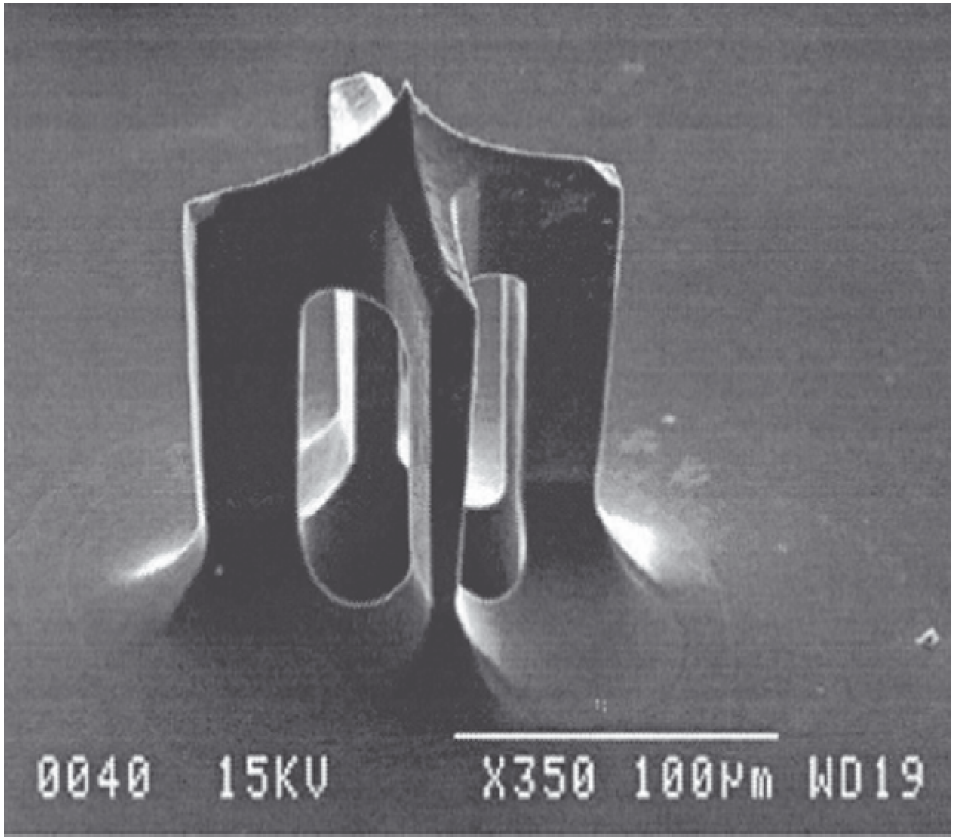

Figure 1.13 Silicon microneedle, about 100 µm. Reproduced from Griss and Stemme (2003), Copyright 2003, by permission of IEEE

Micromechanics

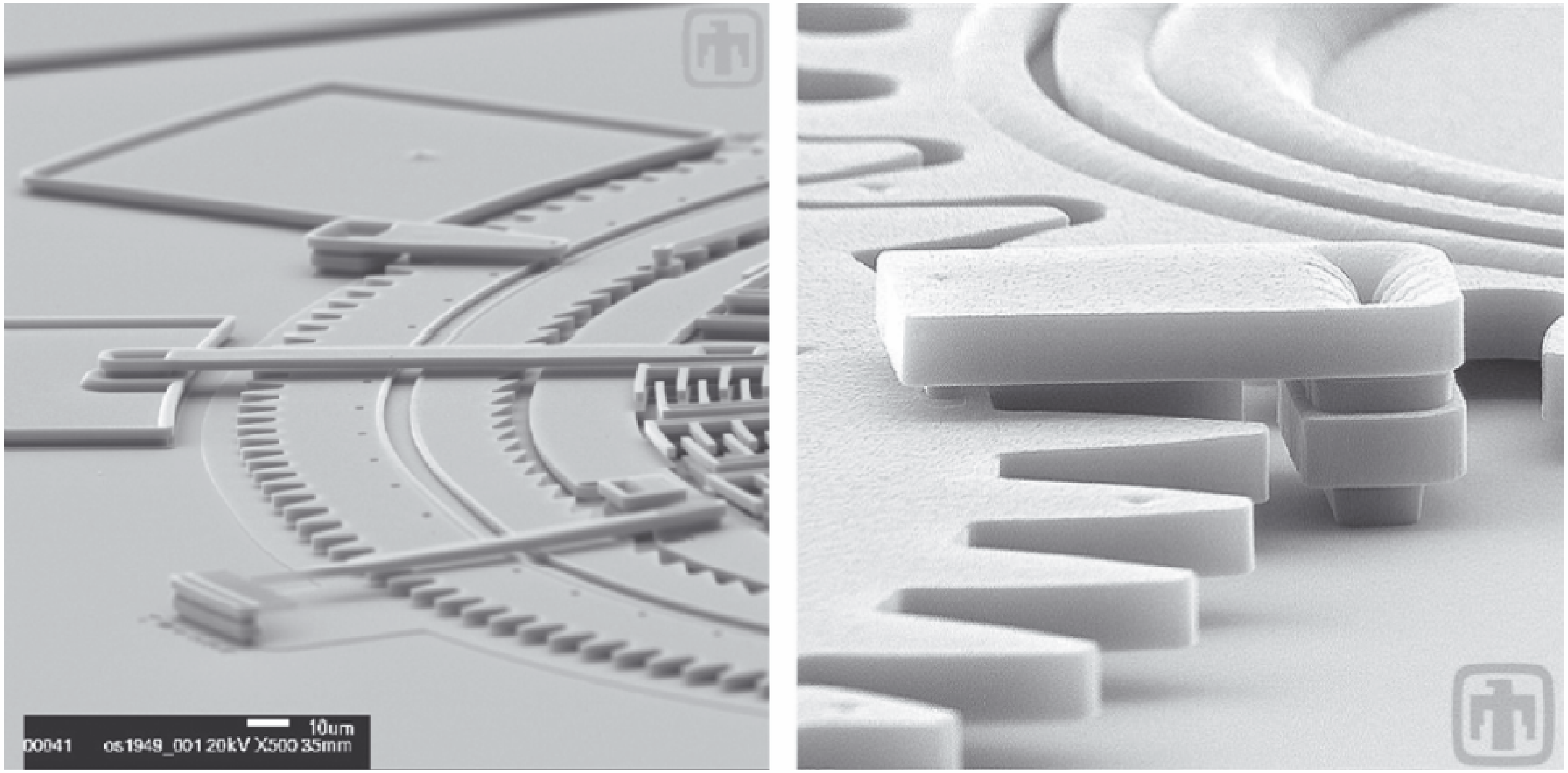

Figure 29.20 Mechanical gears made in multiple layer polysilicon process. Courtesy Sandia National Laboratories

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Print, email, or fax this article for free.

Why the future doesn't need us.

Our most powerful 21st-century technologies - robotics, genetic engineering, and nanotech - are threatening to make humans an endangered species.

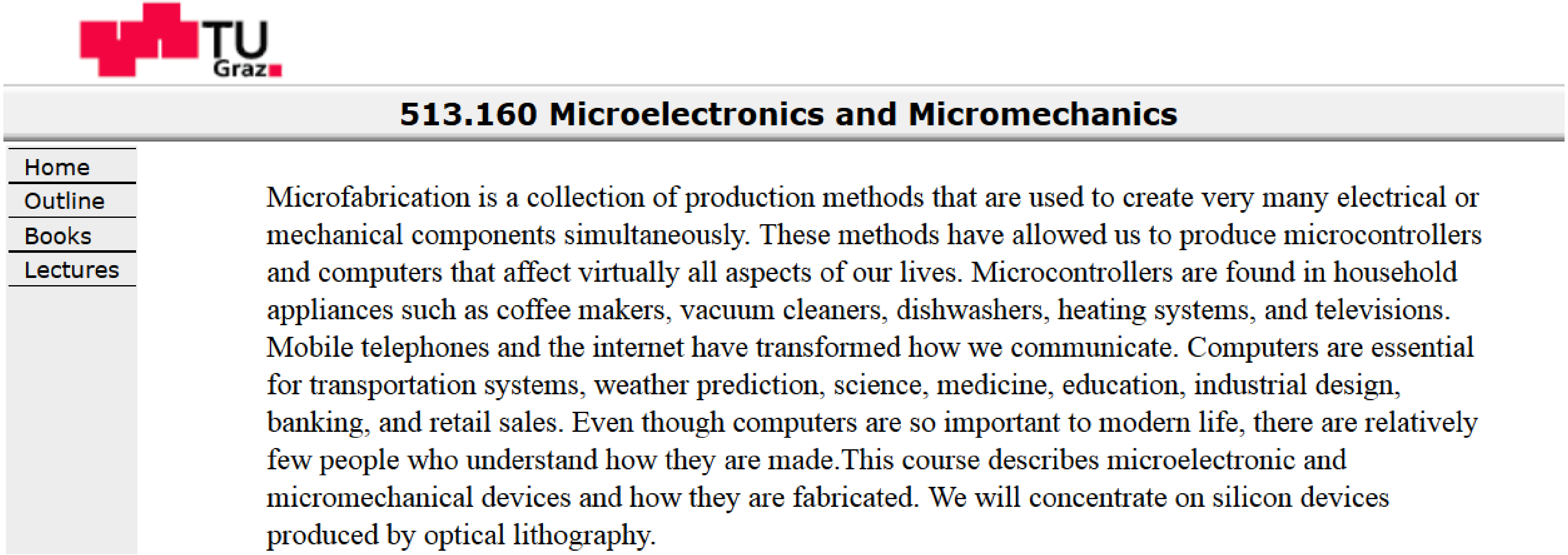
By Bill Joy

PLUS
A Tale of Two Botanies

From the moment I became involved in the creation of new technologies, their ethical dimensions have concerned me, but it was only in the autumn of 1998 that I became anxiously aware of how great are the dangers facing us in the 21st century. I can date the onset of my unease to the day I met Ray Kurzweil, the deservedly famous inventor of the first reading machine for the blind and many other amazing things.

Ray and I were both speakers at George Gilder's Telecosm conference, and I encountered him by chance in the bar of the hotel after both our sessions were over. I was sitting with John Searle, a Berkeley philosopher who studies consciousness. While we were talking, Ray approached and a conversation began, the subject of which haunts me to this day.

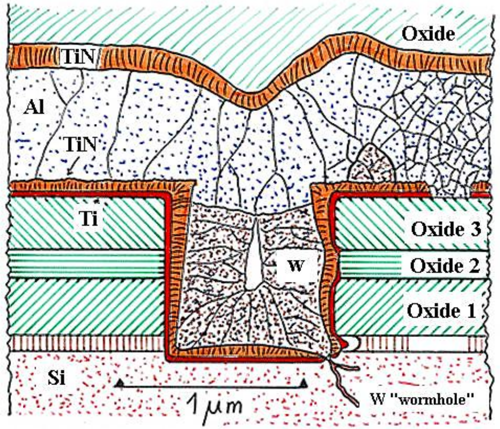
http://www.if.tugraz.at/memm.html



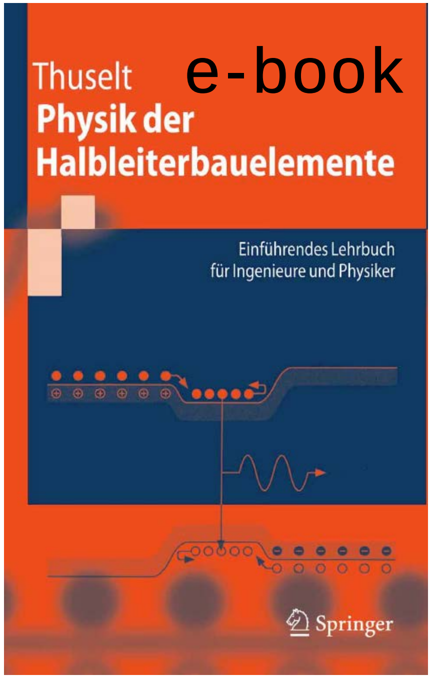
513.160 Microelectronics and Micromechanics

Microfabrication is a collection of production methods that are used to create very many electrical or mechanical components simultaneously. These methods have allowed us to produce microcontrollers and computers that affect virtually all aspects of our lives. Microcontrollers are found in household appliances such as coffee makers, vacuum cleaners, dishwashers, heating systems, and televisions. Mobile telephones and the internet have transformed how we communicate. Computers are essential for transportation systems, weather prediction, science, medicine, education, industrial design, banking, and retail sales. Even though computers are so important to modern life, there are relatively few people who understand how they are made.This course describes microelectronic and micromechanical devices and how they are fabricated. We will concentrate on silicon devices produced by optical lithography.

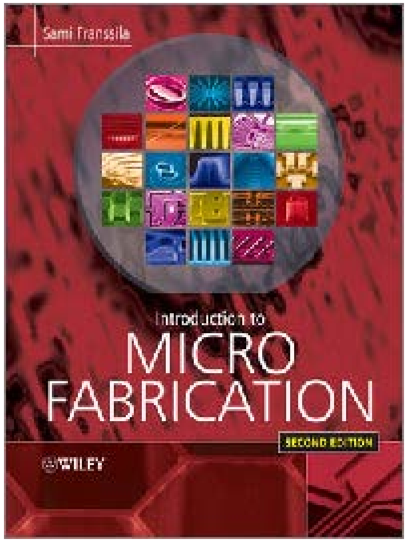
Books



Electronic Materials



e-book



Principles of

Semiconductor Devices

by

Bart Van Zeghbroeck

e-book

ITRS

International Technology Roadmap for Semiconductors

Outline

- **Introduction**
    - The evolution of microelectronics
    - Moore's law
    - Why the future doesn't need us
- **Semiconductors and semiconductor devices**
    - Intrinsic semiconductors
    - Extrinsic semiconductors
    - pn-junctions
    - metal-semiconductor contacts
    - MOSFETs
    - CMOS
    - Memories
    - Semiconducting heterostructures
- **Crystal and thin film growth**
    - Purification of silicon
    - Czochralski process
    - Float Zone process
    - Molecular beam epitaxy
    - Chemical vapor deposition
    - Atomic layer deposition
    - Laser ablation
    - Thermal evaporation
    - Sputtering

Evaluation

July 2

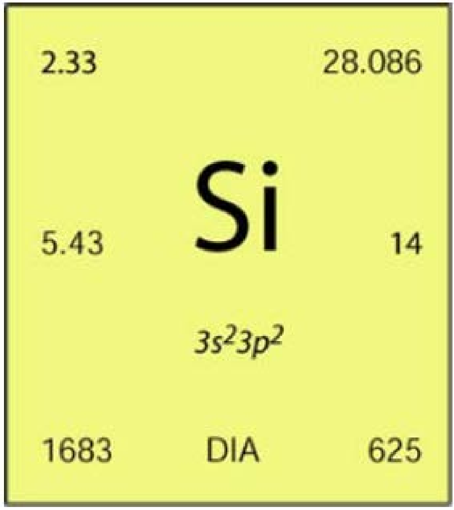
Bring your phone (or a laptop).

Examination

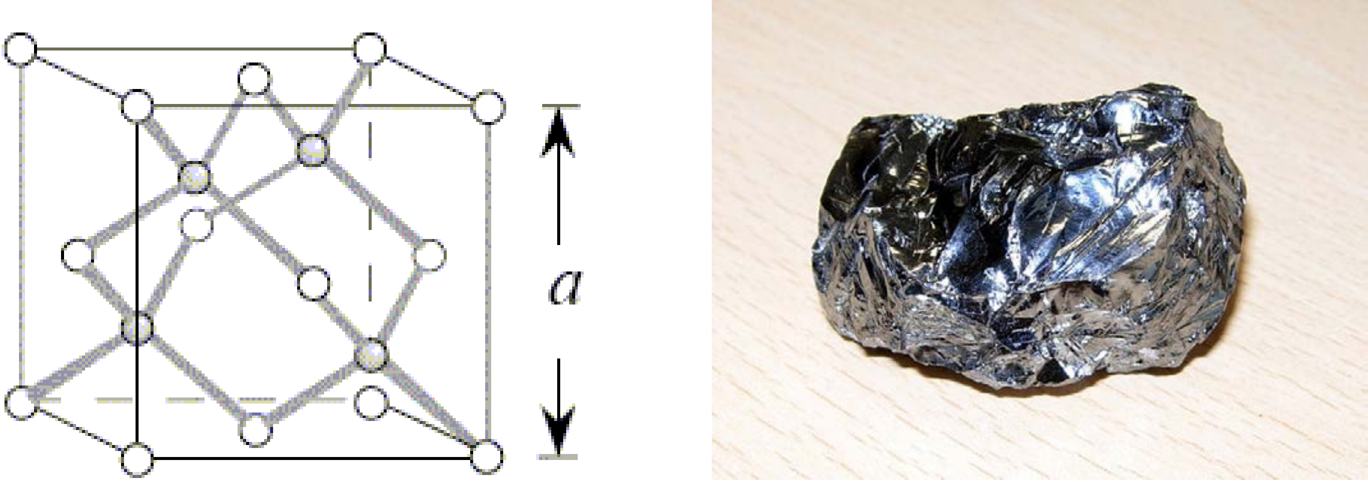
1 Contribution to improve the course

Oral exam

Silicon



- Important semiconducting material
- 2nd most common element on earths crust (rocks, sand, glass, concrete)
- Often doped with other elements
- Oxide SiO_2 is a good insulator



silicon crystal = diamond crystal structure

Franssila

4

Silicon

he first transistor was made of polycrystalline germa-
um in 1947. Electron mobility in germanium is higher
an in silicon, and germanium was readily available.
owever, silicon, with its larger band gap, was favoured
ecause of smaller leakage currents. Initially there was
consensus whether single crystalline or polycrystalline
aterial was better, but the rapid development of sin-
e crystal silicon growth in the 1950's soon dominated
e market. The real breakthrough came when the bene-
cial role of silicon dioxide was recognized: it provided
ssivation of semiconductor surfaces, and it resulted in
nproved transistor reliability. When it was further no-
ced that the SiO_2 layer could act as a diffusion mask
nd as isolation for integrated metallization, the way was
pen for the invention of the integrated circuit.

multicrystalline silicon! As short forms, c-Si is used for crystalline silicon and a-Si for amorphous silicon, while polycrystalline silicon is known simply as poly. In the solar cell industry crystalline silicon is sometimes called X-Si.

4.1 Silicon Material Properties

Silicon material properties are an excellent compromise between performance and stability. An energy gap of 1.12 eV makes silicon devices less prone to thermal noise than germanium devices with a 0.67 eV gap. Silicon is transparent in the infrared (above 1.1 μm wavelength) which means that it can used as an optical material at 1.55 μm telecom wavelength applications.

Silicon

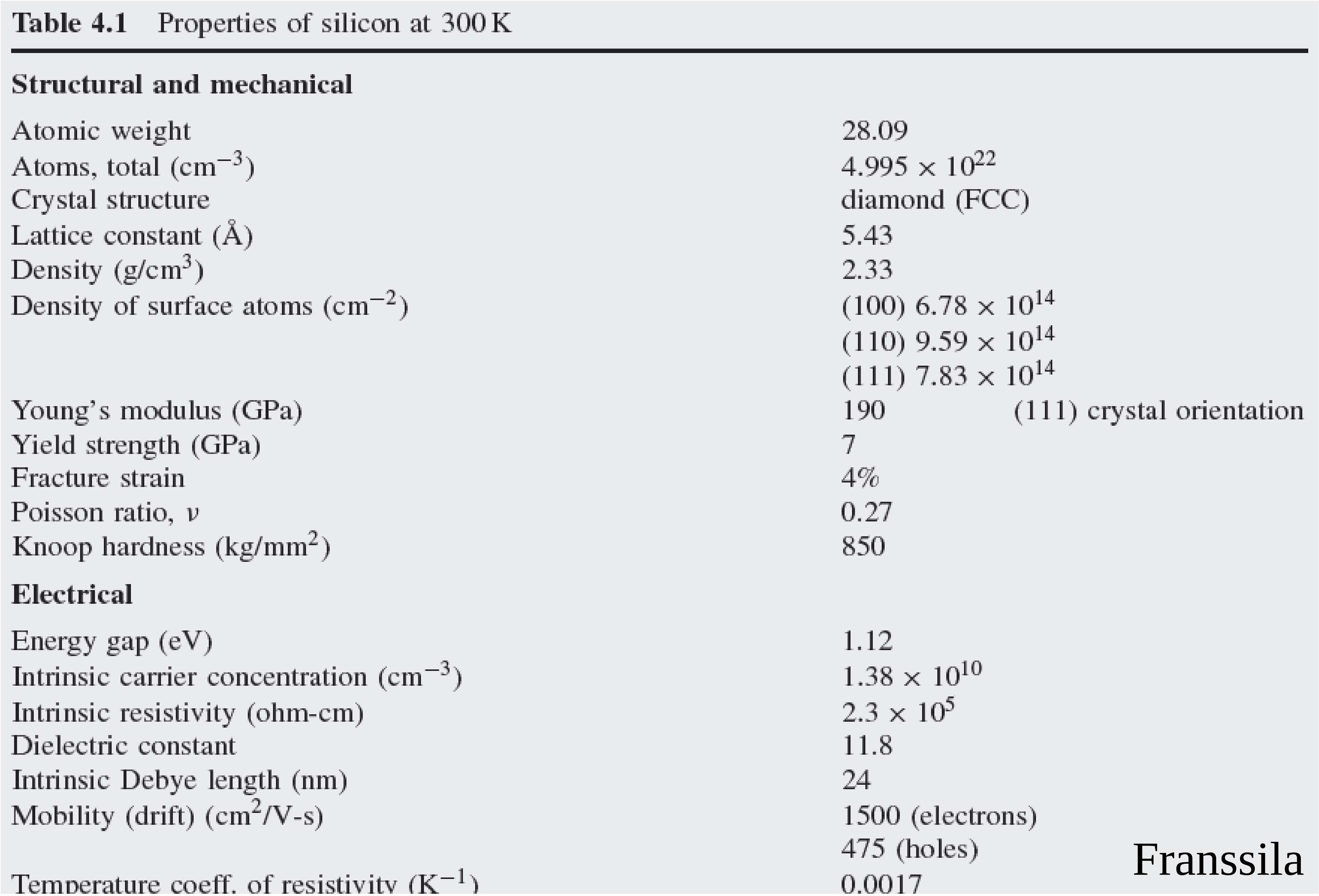


Table 4.1 Properties of silicon at 300 K

Structural and mechanical		
Atomic weight	28.09	
Atoms, total (cm^{-3})	4.995×10^{22}	
Crystal structure	diamond (FCC)	
Lattice constant (Å)	5.43	
Density (g/cm^3)	2.33	
Density of surface atoms (cm^{-2})	(100) 6.78×10^{14} (110) 9.59×10^{14} (111) 7.83×10^{14}	
Young's modulus (GPa)	190	(111) crystal orientation
Yield strength (GPa)	7	
Fracture strain	4%	
Poisson ratio, ν	0.27	
Knoop hardness (kg/mm^2)	850	
Electrical		
Energy gap (eV)	1.12	
Intrinsic carrier concentration (cm^{-3})	1.38×10^{10}	
Intrinsic resistivity (ohm-cm)	2.3×10^5	
Dielectric constant	11.8	
Intrinsic Debye length (nm)	24	
Mobility (drift) (cm^2/V-s)	1500 (electrons) 475 (holes)	
Temperature coeff. of resistivity (K^{-1})	0.0017	

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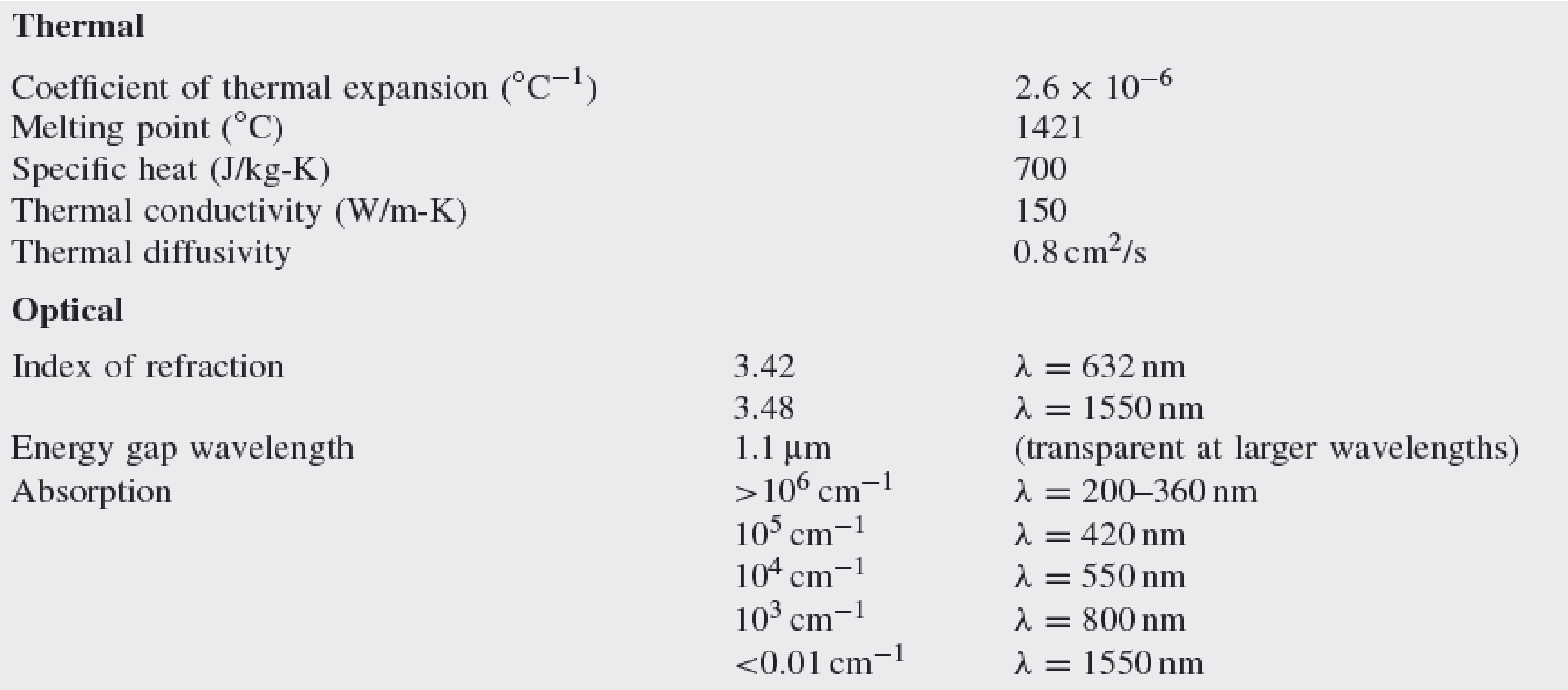
Silicon



Thermal		
Coefficient of thermal expansion (°C^{-1})		2.6×10^{-6}
Melting point (°C)		1421
Specific heat (J/kg-K)		700
Thermal conductivity (W/m-K)		150
Thermal diffusivity		$0.8\ cm^2/s$
Optical		
Index of refraction	3.42	$\lambda = 632$ nm
	3.48	$\lambda = 1550$ nm
Energy gap wavelength	1.1 µm	(transparent at larger wavelengths)
Absorption	$>10^6\ cm^{-1}$	$\lambda = 200$–360 nm
	$10^5\ cm^{-1}$	$\lambda = 420$ nm
	$10^4\ cm^{-1}$	$\lambda = 550$ nm
	$10^3\ cm^{-1}$	$\lambda = 800$ nm
	$<0.01\ cm^{-1}$	$\lambda = 1550$ nm

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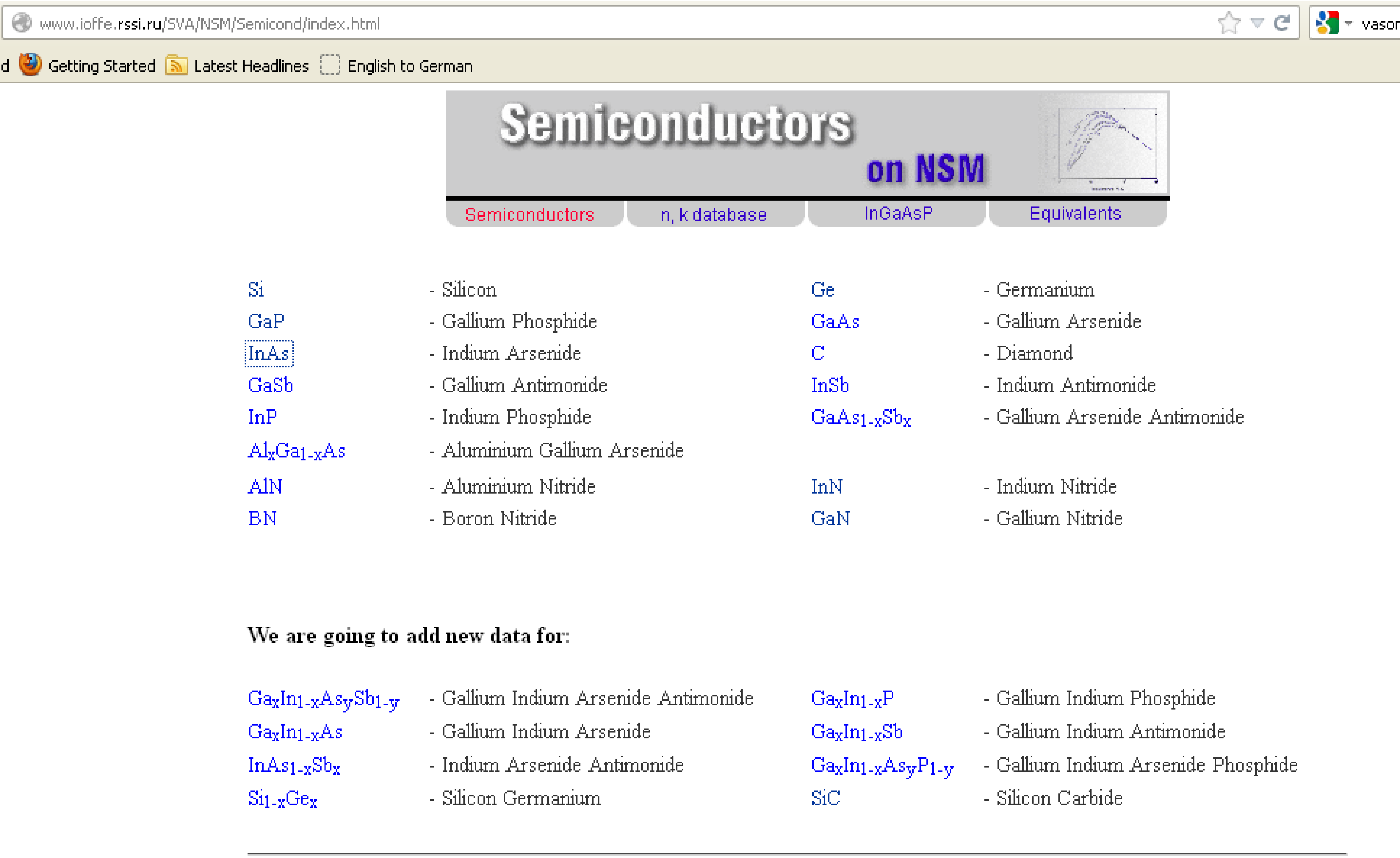


Si	- Silicon	Ge	- Germanium
GaP	- Gallium Phosphide	GaAs	- Gallium Arsenide
InAs	- Indium Arsenide	C	- Diamond
GaSb	- Gallium Antimonide	InSb	- Indium Antimonide
InP	- Indium Phosphide	$GaAs_{1-x}Sb_x$	- Gallium Arsenide Antimonide
$Al_xGa_{1-x}As$	- Aluminium Gallium Arsenide		
AlN	- Aluminium Nitride	InN	- Indium Nitride
BN	- Boron Nitride	GaN	- Gallium Nitride

We are going to add new data for:

$Ga_xIn_{1-x}As_ySb_{1-y}$	- Gallium Indium Arsenide Antimonide	$Ga_xIn_{1-x}P$	- Gallium Indium Phosphide
$Ga_xIn_{1-x}As$	- Gallium Indium Arsenide	$Ga_xIn_{1-x}Sb$	- Gallium Indium Antimonide
$InAs_{1-x}Sb_x$	- Indium Arsenide Antimonide	$Ga_xIn_{1-x}As_yP_{1-y}$	- Gallium Indium Arsenide Phosphide
$Si_{1-x}Ge_x$	- Silicon Germanium	SiC	- Silicon Carbide

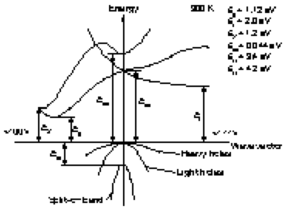
http://www.ioffe.rssi.ru/SVA/NSM/Semicond/Si/bandstr.html

Si - Silicon

Band structure and carrier concentration

Basic Parameters

Energy gap	1.12 eV
Energy separation ($E_{\Gamma L}$)	4.2 eV
Energy spin-orbital splitting	0.044 eV
Intrinsic carrier concentration	$1\cdot10^{10}$ cm^{-3}
Intrinsic resistivity	$3.2\cdot10^{5}\,\Omega\cdot$cm
Effective conduction band density of states	$3.2\cdot10^{19}$ cm^{-3}
Effective valence band density of states	$1.8\cdot10^{19}$ cm^{-3}



Band structure of Si at 300 K.
$E_g = 1.12$ eV
$E_L = 2.0$ eV
$E_X = 1.2$ eV
$E_{so} = 0.044$ eV
$E_{\Gamma1} = 3.4$ eV
$E_{\Gamma2} = 4.2$ eV

Temperature Dependences

Temperature dependence of the energy gap

$E_g = 1.17 - 4.73\cdot10^{-4}\cdot T^2/(T+636)$ (eV),
where T is temperature in degrees K.

Temperature dependence of the direct band gap $E_{\Gamma2}$

$E_{\Gamma2} = 4.34 - 3.91\cdot10^{-4}\cdot T^2/(T+125)$ (eV)

Intrinsic carrier concentration

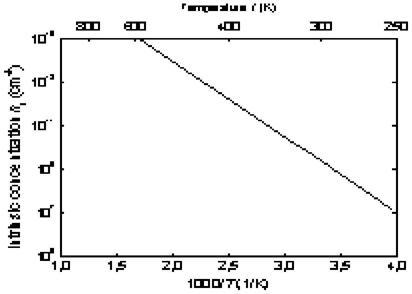
$n_i=(N_c\cdot N_v)^{1/2}\cdot\exp(-Eg/(2k_BT))$

Effective density of states in the conduction band

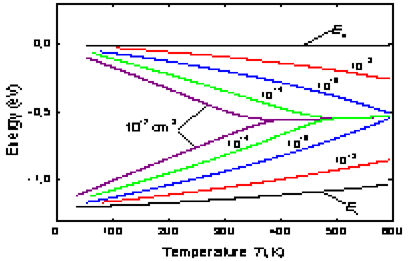
$N_c=4.82\cdot10^{15}\cdot M\cdot(m_c/m_o)^{3/2}\cdot T^{3/2} = 4.82\cdot10^{15}\cdot M\cdot(m_{cd}/m_o)^{3/2}\cdot T^{3/2}$ (cm^{-3}),
or
$N_c=6.2\cdot10^{15}\cdot T^{3/2}$ (cm^{-3}),
$M = 6$ is the number of equivalent valleys in the conduction band.
$m_c = 0.36m_o$ is the effective mass of the density of states in one valley of conduction
$m_{cd} = 1.18m_o$ is the effective mass of the density of states.

Effective density of states in the valence band

$N_v = 3.5\cdot10^{15}\cdot T^{3/2}$ (cm^{-3}).



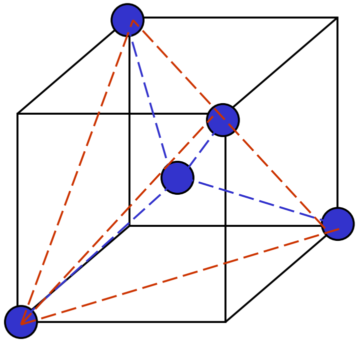
The temperature dependence of the intrinsi
(Shur [1990]).



Fermi level versus temperature for differen
(Grove [1967]).

diamond

C
Si
Ge



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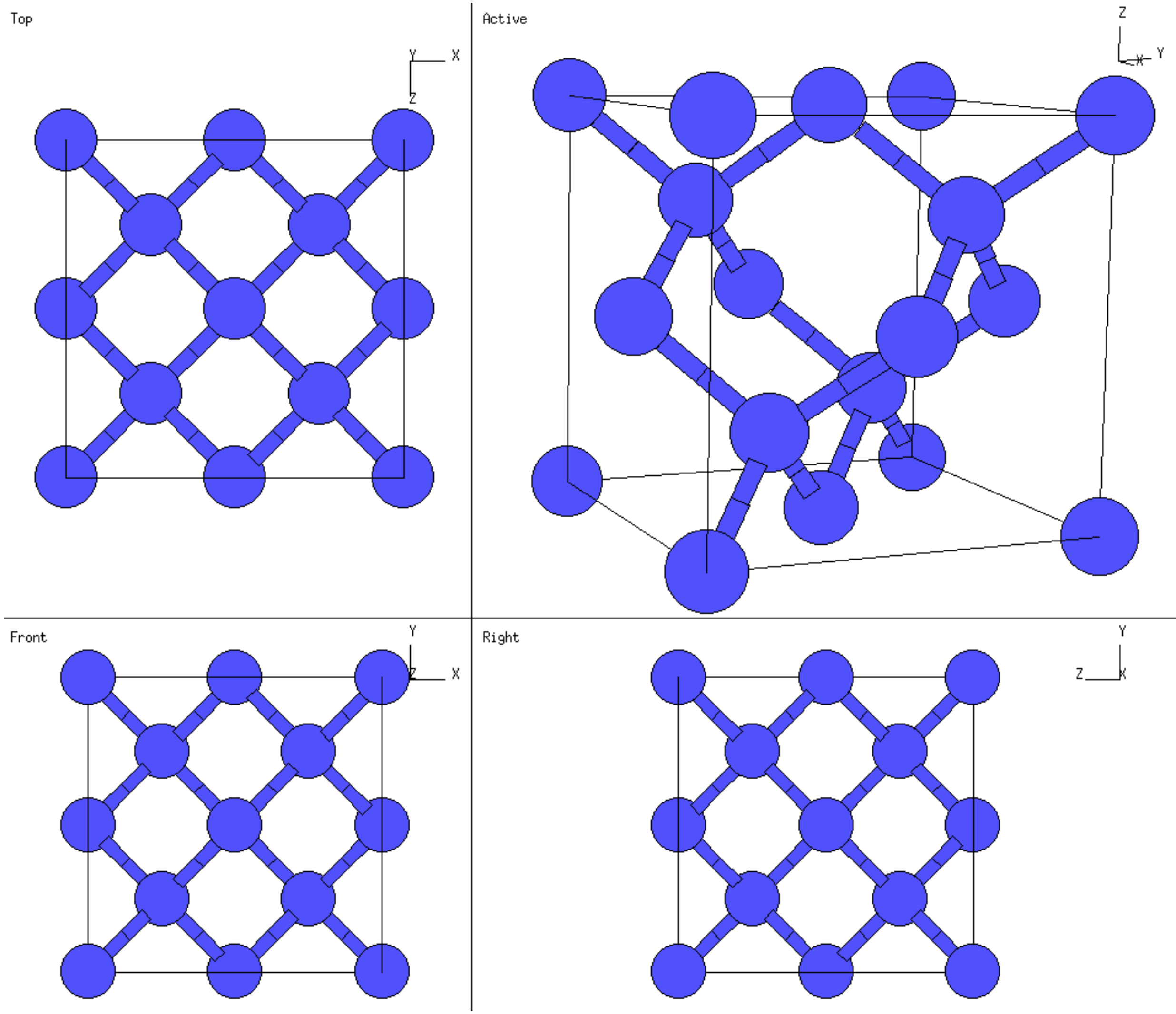


- Primitive Vectors:

$$\vec{a}_1 = \frac{a}{2}\hat{y} + \frac{a}{2}\hat{z}$$

$$\vec{a}_2 = \frac{a}{2}\hat{x} + \frac{a}{2}\hat{z}$$

$$\vec{a}_3 = \frac{a}{2}\hat{x} + \frac{a}{2}\hat{y}$$

$a = 0.543$ nm

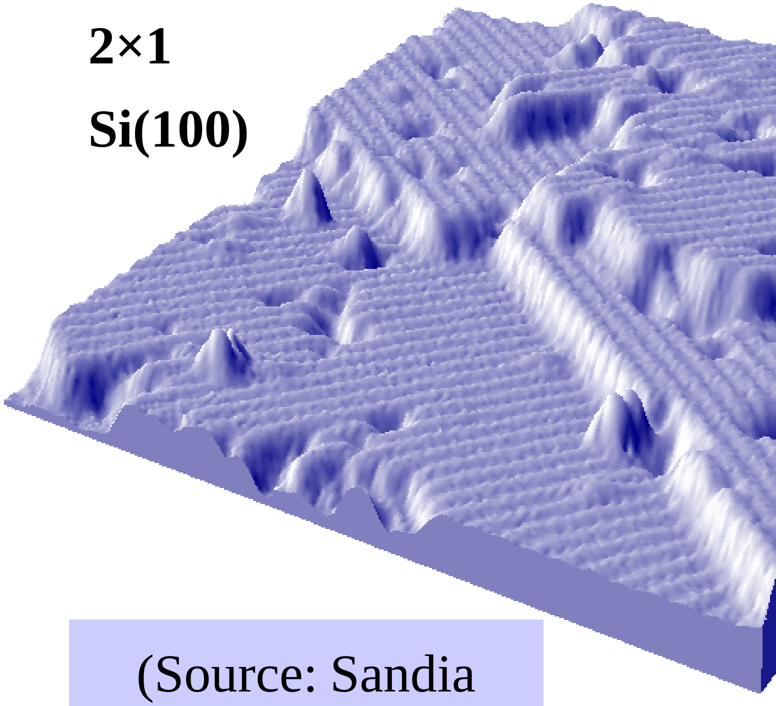
- Basis Vectors:

$$\vec{B}_1 = (0,0,0)$$

$$\vec{B}_2 = (1/4,1/4,1/4)$$

Point group: m3m (O_h) 6 2-fold rotations, 4 3-fold rotations, 3 4-fold rotations, 9 mirror planes, inversion

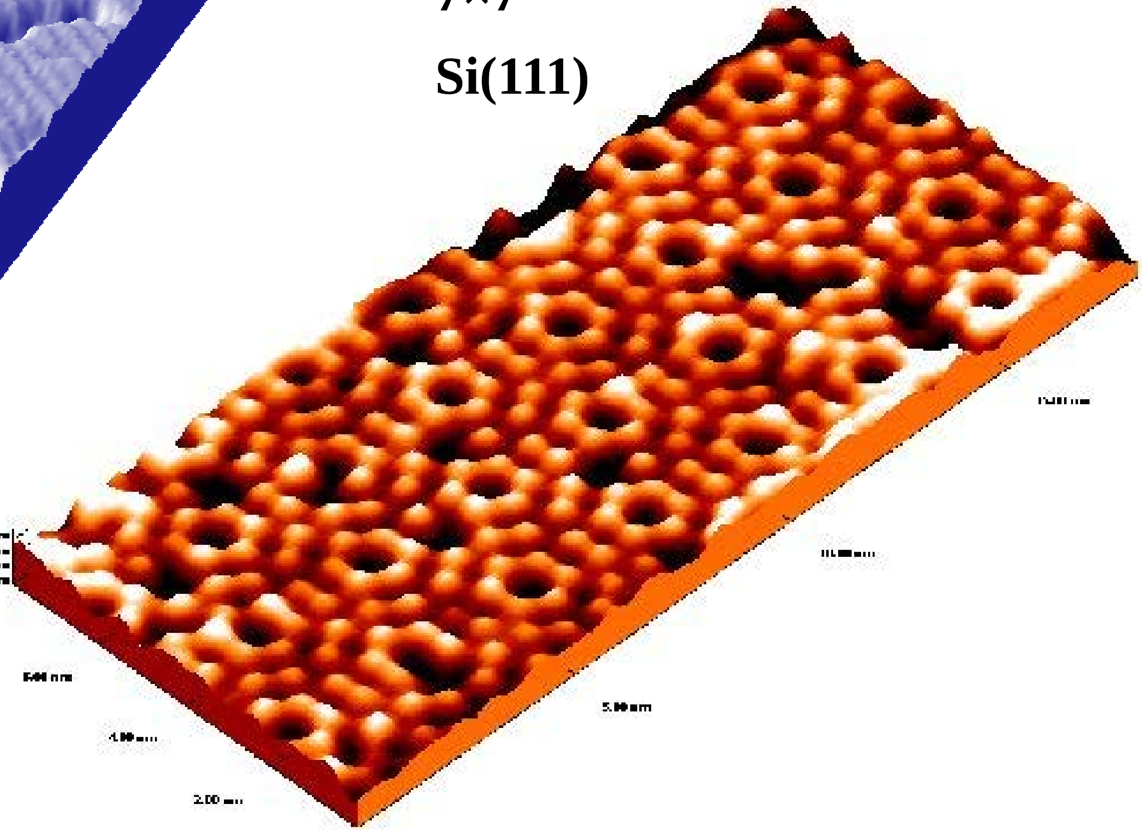
Silicon surfaces



2×1

Si(100)

(Source: Sandia Nat.Labs.)



7×7

Si(111)

Density of surface atoms

$(100)\ 6.78 \times 10^{14}\ 1/\text{cm}^2$

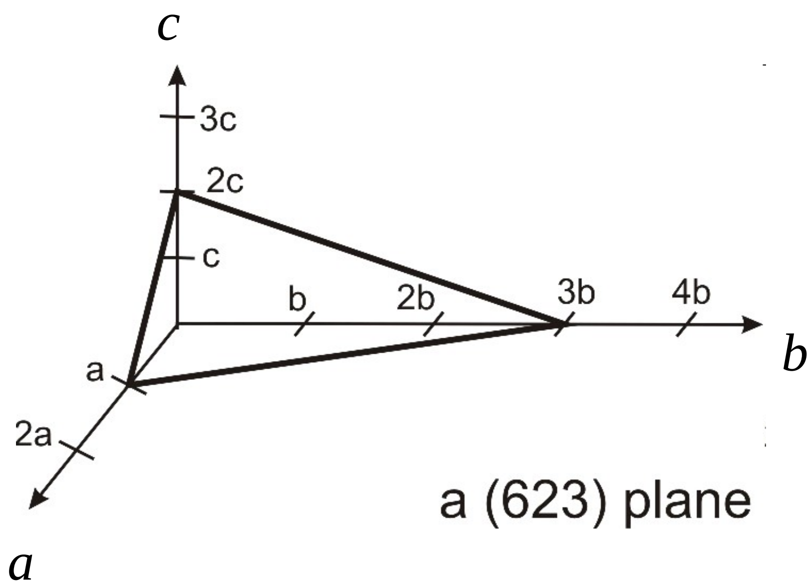
$(110)\ 9.59 \times 10^{14}\ 1/\text{cm}^2$

$(111)\ 7.83 \times 10^{14}\ 1/\text{cm}^2$

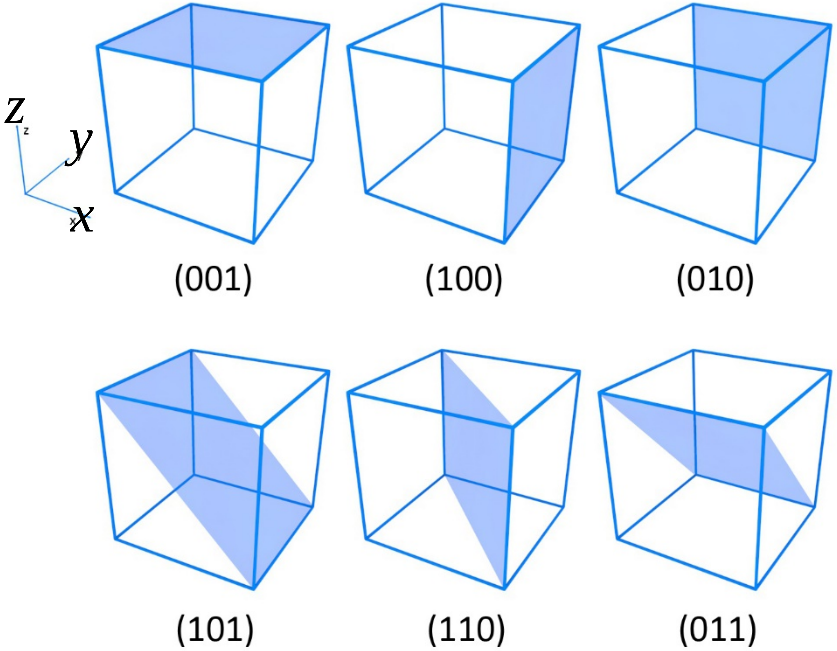
Miller indices: Crystal planes

A plane with the intercepts 1/*h*,1/*k*,1/*l* is the (*h*,*k*,*l*) plane.

always use integers for *h*,*k*,*l*



( ) specific plane
{ } family of equivalent planes



MOSFETs are made on <100> wafers

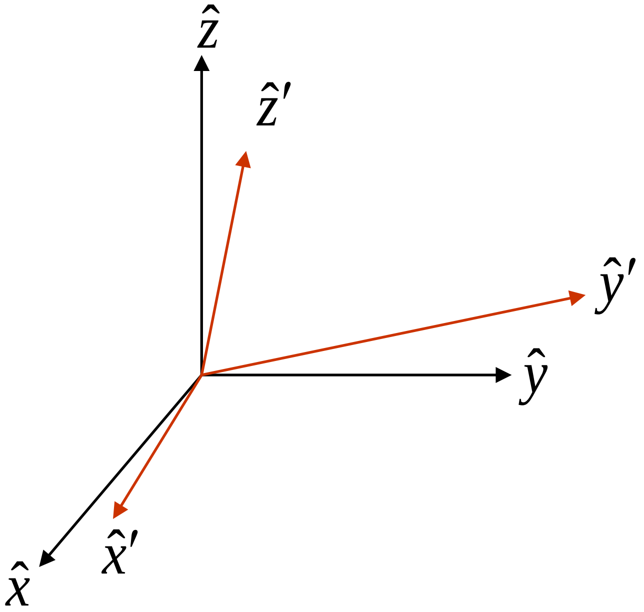
Strain

A distortion of a material is described by the strain matrix

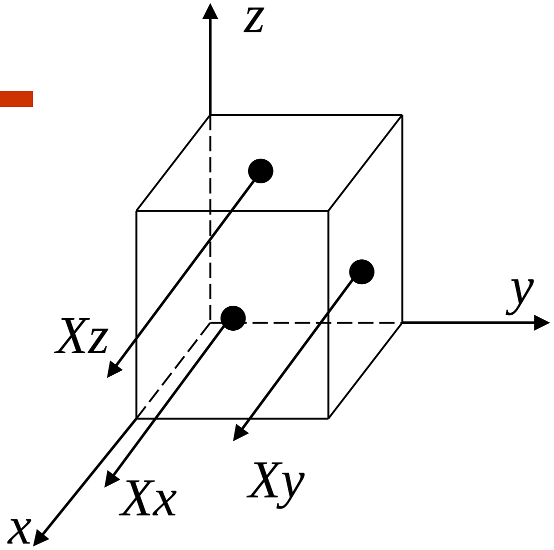
$$x' = (1+\varepsilon_{xx})\hat{x} + \varepsilon_{xy}\hat{y} + \varepsilon_{xz}\hat{z}$$

$$y' = \varepsilon_{yx}\hat{x} + (1+\varepsilon_{yy})\hat{y} + \varepsilon_{yz}\hat{z}$$

$$z' = \varepsilon_{zx}\hat{x} + \varepsilon_{zy}\hat{y} + (1+\varepsilon_{zz})\hat{z}$$



Stress



9 forces describe the stress

Xx, Xy, Xz, Yx, Yy, Yz, Zx, Zy, Zz

Xx is a force applied in the *x*-direction to the plane normal to *x*

Xy is a sheer force applied in the *x*-direction to the plane normal to *y*

stress tensor:

$$\sigma = \begin{bmatrix} \frac{X_x}{A_x} & \frac{X_y}{A_y} & \frac{X_z}{A_z} \\ \frac{Y_x}{A_x} & \frac{Y_y}{A_y} & \frac{Y_z}{A_z} \\ \frac{Z_x}{A_x} & \frac{Z_y}{A_y} & \frac{Z_z}{A_z} \end{bmatrix}$$

Stress is force/m^2

Stress and Strain

$$\varepsilon_{ij} = s_{ijkl}\sigma_{kl}$$

The stress - strain relationship is described by a rank 4 stiffness tensor. The inverse of the stiffness tensor is the compliance tensor.

$$\sigma_{ij} = c_{ijkl}\varepsilon_{kl}$$

Einstein convention: sum over repeated indices.

$$\varepsilon_{xx} = s_{xxxx}\sigma_{xx} + s_{xxxy}\sigma_{xy} + s_{xxxz}\sigma_{xz} + s_{xxyx}\sigma_{yx} + s_{xxyy}\sigma_{yy}$$
$$+ s_{xxyz}\sigma_{yz} + s_{xxzx}\sigma_{zx} + s_{xxzy}\sigma_{zy} + s_{xxzz}\sigma_{zz}$$

Mechanical properties

The stress-strain relation for silicon is described by the tensor equation,

$$\sigma_{ij} = c_{ijkl}\epsilon_{kl},$$

where the elements of the compliance tensor are,

$c_{11} = 165.7 \text{ GPa} = c_{xxxx} = c_{yyyy} = c_{zzzz},$
$c_{12} = 63.9 \text{ GPa} = c_{xxyy} = c_{xxzz} = c_{zzyy} = c_{yyxx} = c_{yyzz} = c_{zzxx},$
$c_{44} = 79.6 \text{ GPa} = c_{xyxy} = c_{xzxz} = c_{yzyz} = c_{yxyx} = c_{zxzx} = c_{zyzy},$
all other components $c_{ijkl} = 0.$

Yield strength: 7 GPa
Fracture strain: 4%
Possion's ratio: 0.27

When an electric field is applied to a silicon crystal, the resulting strain can be expressed as a Taylor series,

$$\epsilon_{ij} = d_{ijk}E_k + Q_{ijkl}E_kE_l + \cdots,$$

where ϵ_{ij} is the strain, E_k is the electric field, d_{ijk} is the reciprocal piezoelectric tensor, and Q_{ijkl} is the electrostriction tensor. Silicon has inversion symmetry in its point group so the reciprocal piezoelectric tensor is zero by symmetry and the leading order term is electrostriction.