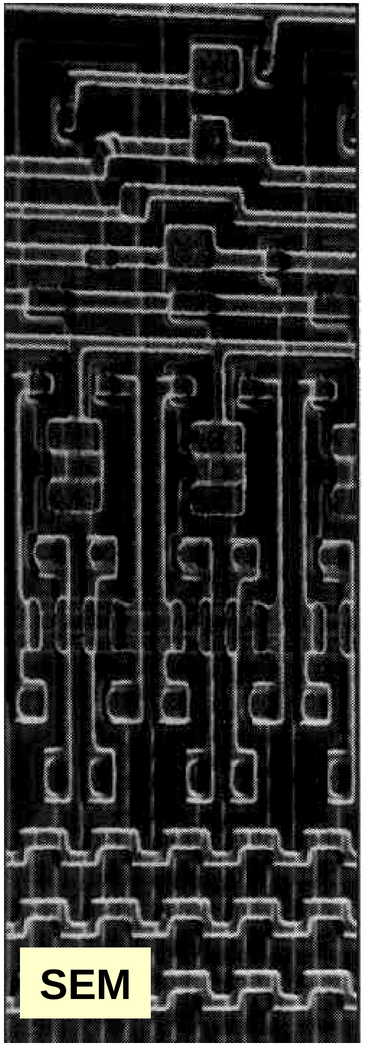
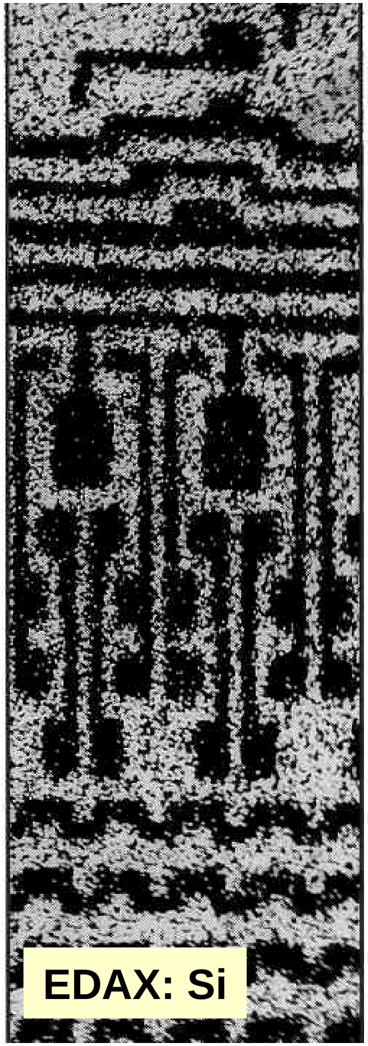
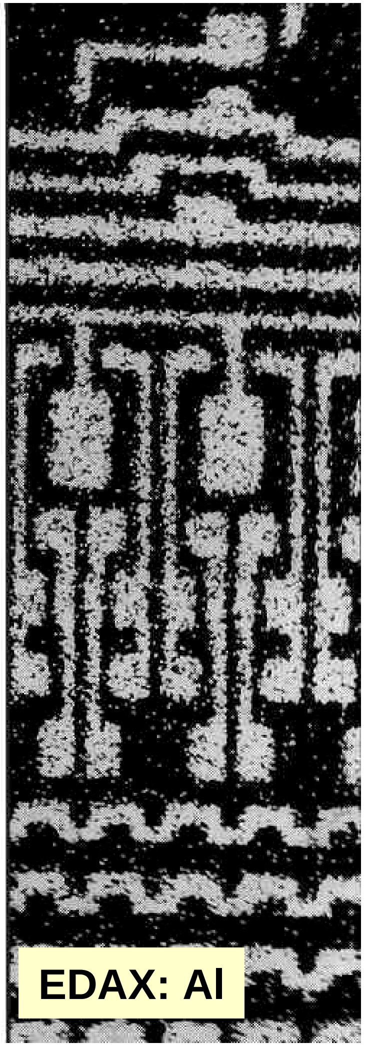
Semiconductors


SEM

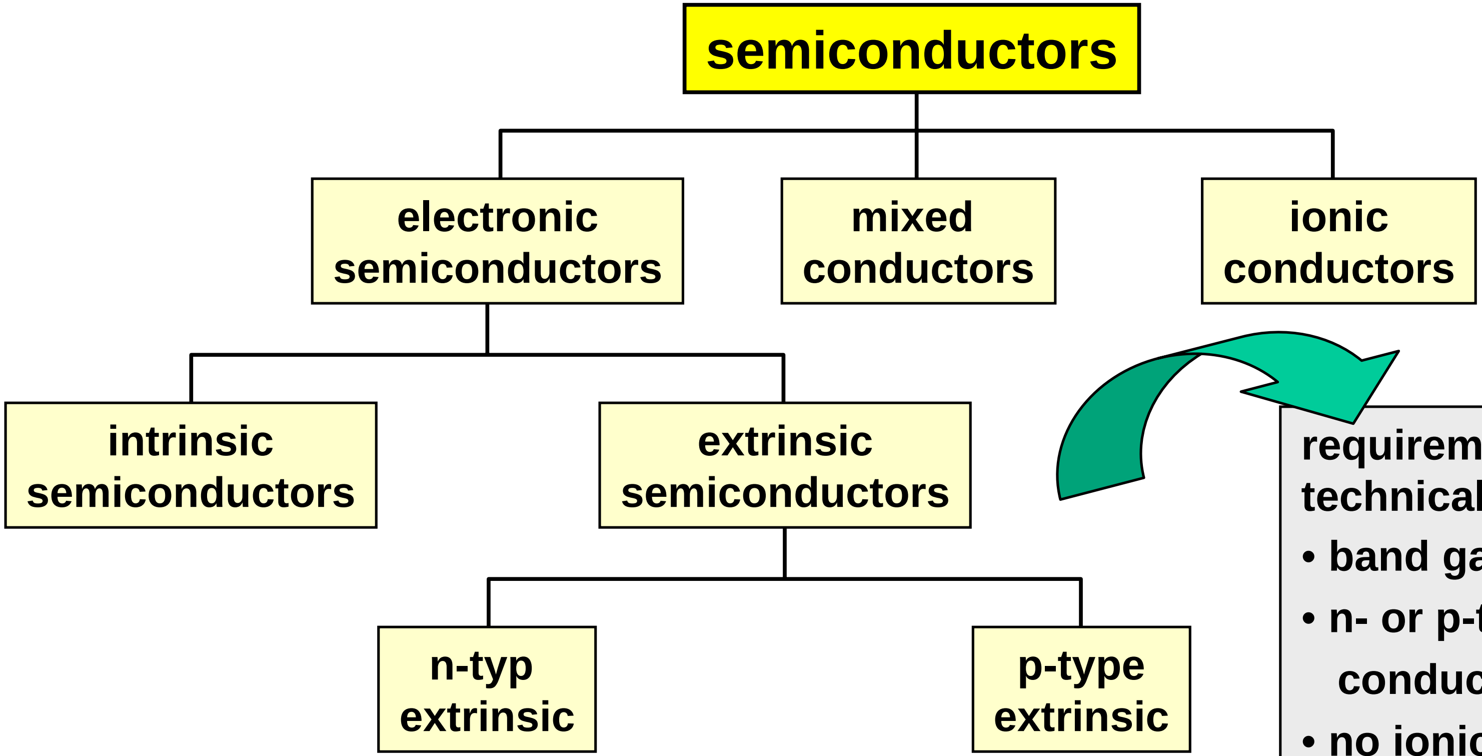

EDAX: Si


EDAX: Al

SEM and EDAX images of an integrated circuit

source: [Cal 99 / 605]

Semiconductors
Classification



requirements for technical applications:

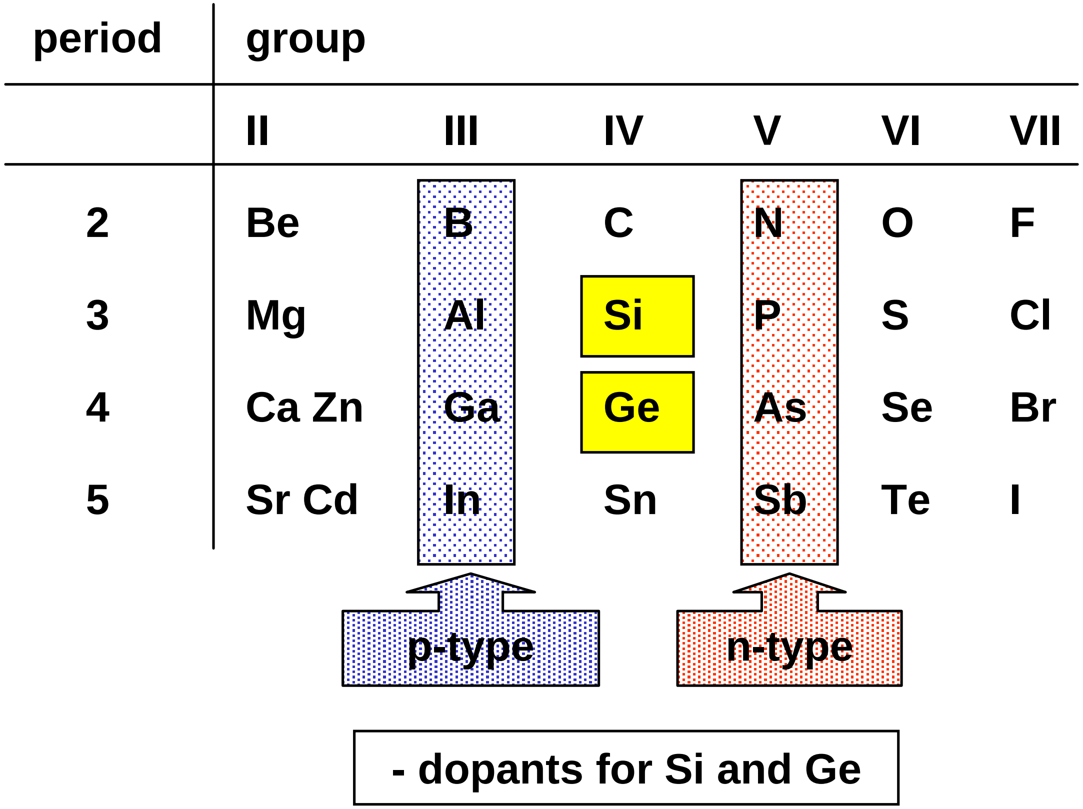
- **band gap 0,1...3 eV**
- **n- or p-type conduction**
- **no ionic conduction**

} covalent bonding

- **chemical and thermal stability**
- **solubility of dopants in the host lattice**

source: [Hahn 73 / 78]

Semiconductors
Elemental Semiconductors and Dopants



period	**group**					
	II	**III**	**IV**	**V**	**VI**	**VII**
2	**Be**	**B**	**C**	**N**	**O**	**F**
3	**Mg**	**Al**	**Si**	**P**	**S**	**Cl**
4	**Ca Zn**	**Ga**	**Ge**	**As**	**Se**	**Br**
5	**Sr Cd**	**In**	**Sn**	**Sb**	**Te**	**I**

- dopants for Si and Ge

band gap E_g / eV
of different semiconductors

	T = 0 K	**T = 300 K**
Si	**1,17**	**1,11**
Ge	**0,74**	**0,68**
GaAs	**1,52**	**1,38**
InAs	**0,36**	**0,35**
InSb	**0,23**	**0,18**
CdS	**2,58**	**2,42**
CdTe	**1,61**	**1,45**
ZnO	**3,44**	**3,20**

source: [Hahn73 / 78]

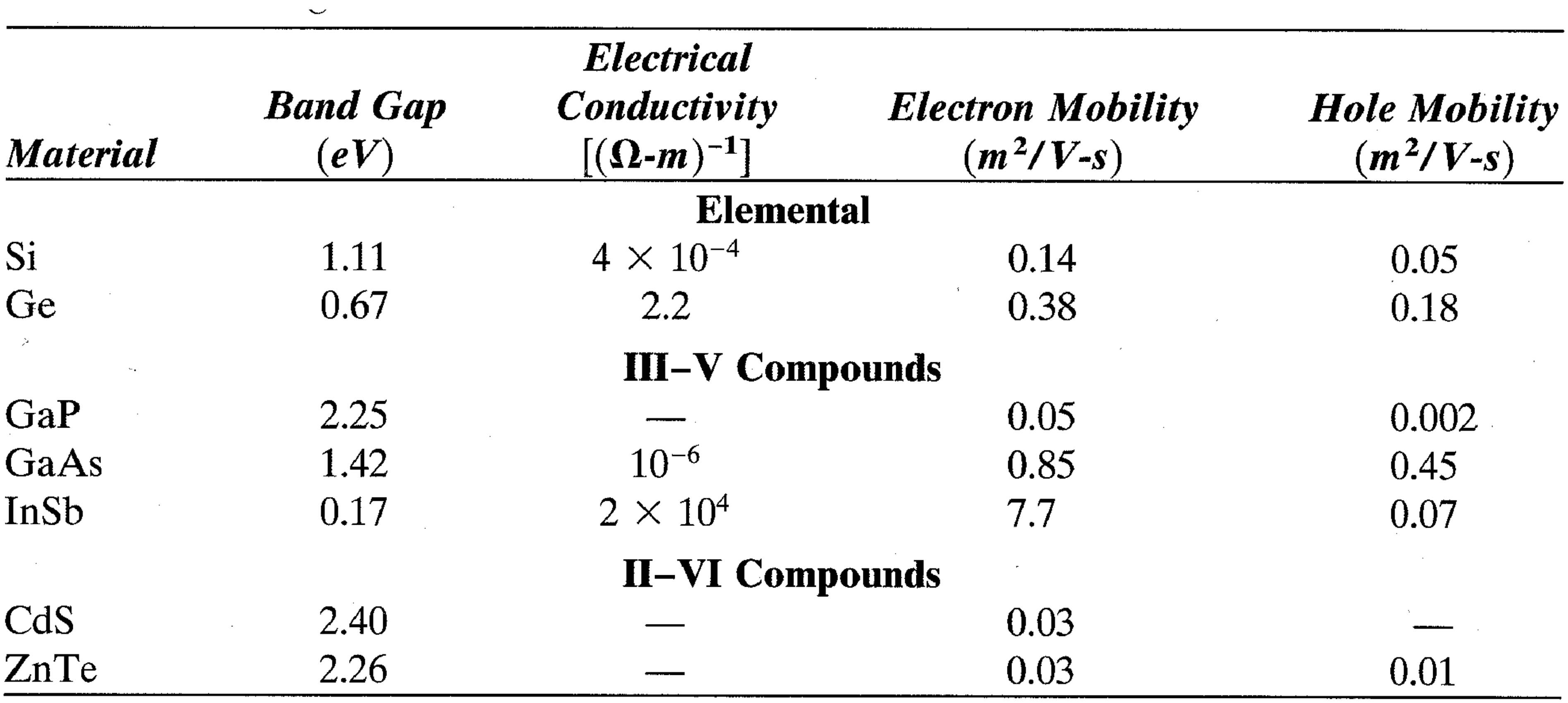
Semiconductors
Elemental and Compound Semiconductors

elemental s.	compound s.		
IV - IV bonding	III - V bonding	II - VI bonding	number of electrons per unit
C			6
SiC			10
Si	AlP		14
GeSi	AlAs, GaP	ZnS	23
Ge	AlSb, GaAs, InP	ZnSe, CdS	32
	GaSb ,InAs	ZnTe, CdSe, HgS	41
Sn	InSb	CdTe, HgSe	50
		HgTe	66

atomic bonding forces become more ionic

source: [Hey 76 / 31]

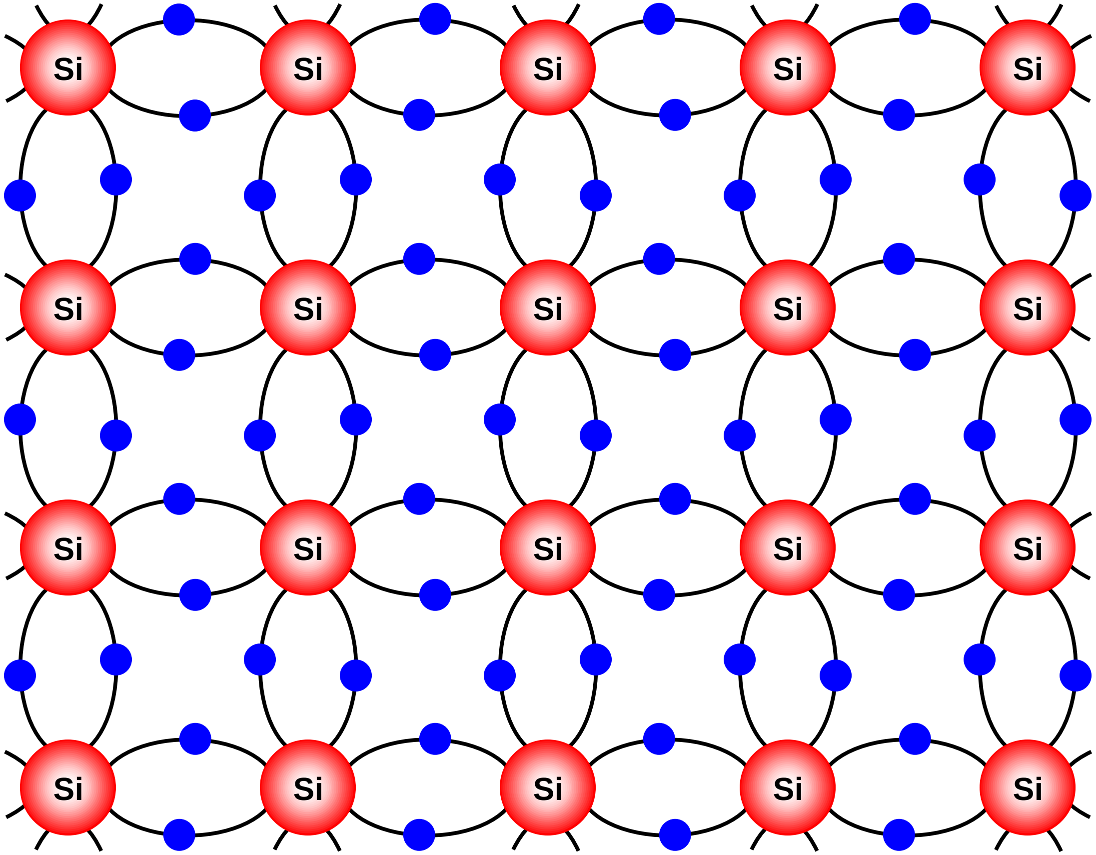
Semiconductors
Properties of Elemental and Compound Semiconductors

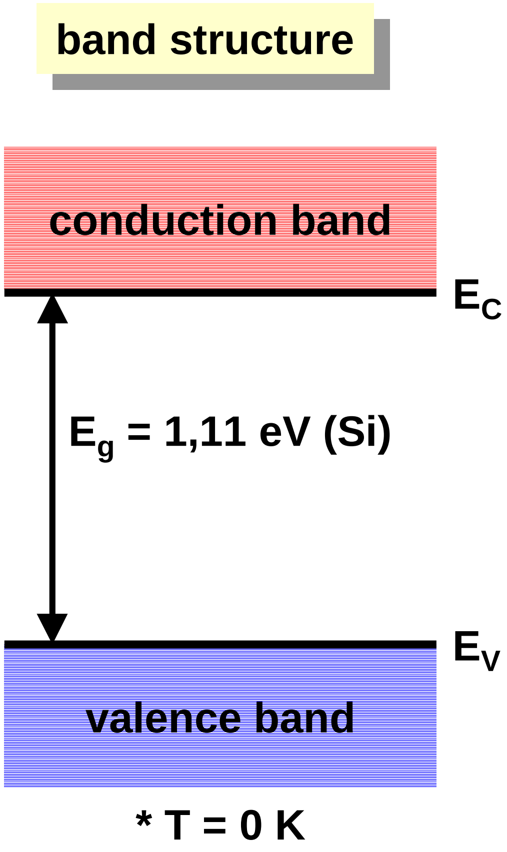


Material	*Band Gap* (eV)	*Electrical Conductivity* $[(\Omega\text{-}m)^{-1}]$	*Electron Mobility* ($m^2/V\text{-}s$)	*Hole Mobility* ($m^2/V\text{-}s$)
		Elemental		
Si	1.11	4×10^{-4}	0.14	0.05
Ge	0.67	2.2	0.38	0.18
		III–V Compounds		
GaP	2.25	—	0.05	0.002
GaAs	1.42	10^{-6}	0.85	0.45
InSb	0.17	2×10^{4}	7.7	0.07
		II–VI Compounds		
CdS	2.40	—	0.03	—
ZnTe	2.26	—	0.03	0.01

source: [Cal 99 / 617]

Semiconductors
Electrical Conduction in Intrinsic Silicon at T = 0 K





band structure

conduction band

E_C

E_g = 1,11 eV (Si)

E_V

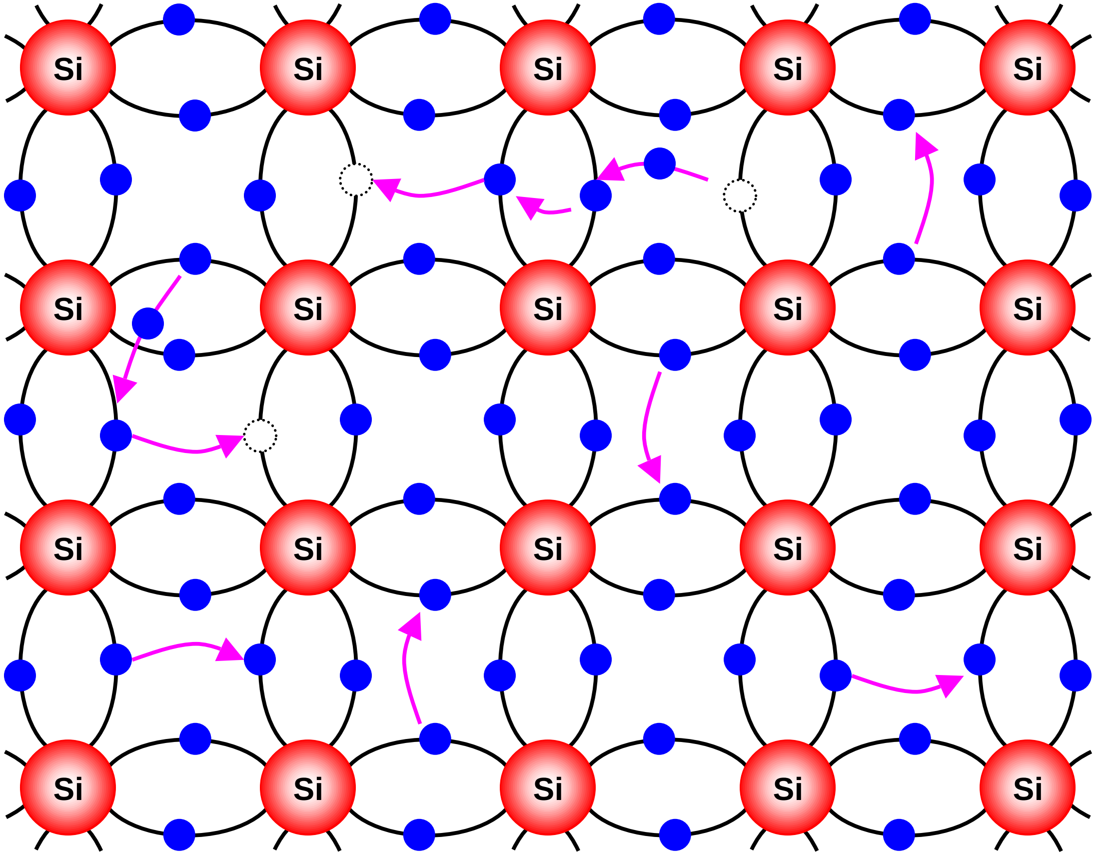
valence band

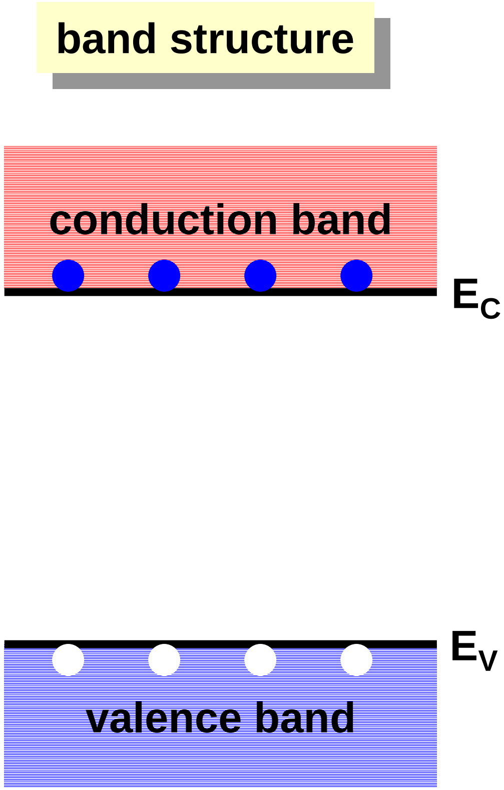
* T = 0 K

Si^{4+} (Ge^{4+}): 4 outer electrons (sp^3-hybride) ⇨ no electrons in the conduction band*

source: IWE

Semiconductors
Electrical Conduction in Intrinsic Silicon at T > 0 K



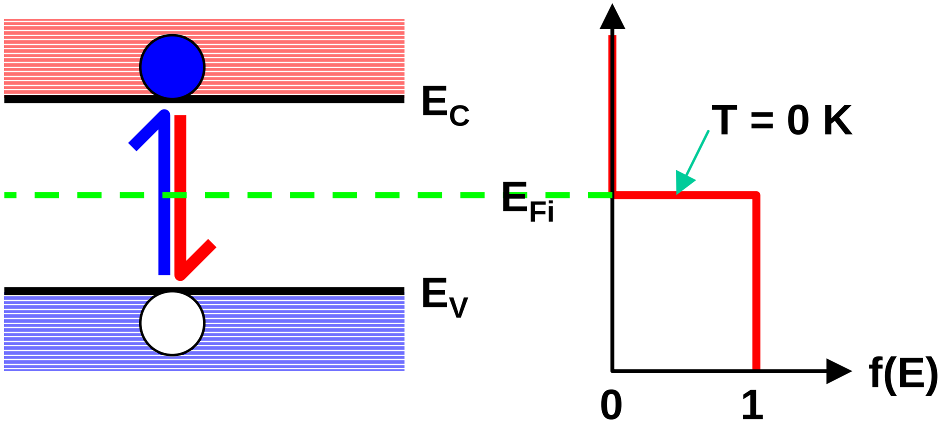


charge carriers at T > 0 K ⇨

- **(mobile) electrons in the conduction band**
- **(mobile) holes in the valence band**

source: IWE

Semiconductors
Charge Carriers in Intrinsic Semiconductors



$$f(E) = \frac{1}{1 + e^{\frac{E - E_{Fi}}{kT}}}$$

E_{Fi}: fermi-level for intrinsic semiconductor

- **thermal equilibrium**

$$0 \; \underset{\text{recombination}}{\overset{\text{generation}}{\rightleftharpoons}} \; e^{-} + h^{+} \qquad\qquad n(T) = p(T)$$

- **intrinsic charge carrier concentration n_i**

$n_i = n = p$

n: (mobile) electrons in the conduction band
p: (mobile) holes in the valence band

source: IWE

Semiconductors
Charge Carrier Concentration and Fermi Level

- **electron concentration n (conduction band)**

$$\boxed{n = N_C \cdot e^{\frac{-(E_C - E_{Fi})}{kT}}}$$

$$N_C = 2 \cdot \left(\frac{2\pi \cdot m_n^* \cdot kT}{h^2} \right)^{\frac{3}{2}}$$

- **hole concentration p (valence band)**

$$\boxed{p = N_V \cdot e^{\frac{-(E_{Fi} - E_V)}{kT}}}$$

$$N_V = 2 \cdot \left(\frac{2\pi \cdot m_p^* \cdot kT}{h^2} \right)^{\frac{3}{2}}$$

- **intrinsic charge carrier concentration n$_i$**

$$\boxed{n_i = N_{eff} \cdot e^{\frac{-E_g}{2kT}}}$$

$$N_{eff} = \sqrt{N_C \cdot N_V}$$

- **fermi level in an intrinsic semiconductor**

$$E_{Fi} = E_V + \frac{1}{2} E_g + \frac{3}{4} kT \cdot \ln \frac{m_p^*}{m_n^*}$$ **with** $E_g = E_C - E_V$ **for** $m_p^* = m_n^*$

$$E_{Fi} = E_V + \frac{1}{2} E_g$$

source: IWE

Semiconductors
Intrinsic Conductivity

- **intrinsic conductivity by excitation of free electron-hole-pairs**

$$\sigma_i = n_i \cdot e_0 \cdot (\mu_n + \mu_p)$$

- **mobility of free electrons and holes**

$$\mu_n = \frac{e_0 \cdot \tau_n}{m_n^*}$$

$$\mu_p = \frac{e_0 \cdot \tau_p}{m_p^*}$$

- **temperature dependence of electron and hole mobility**

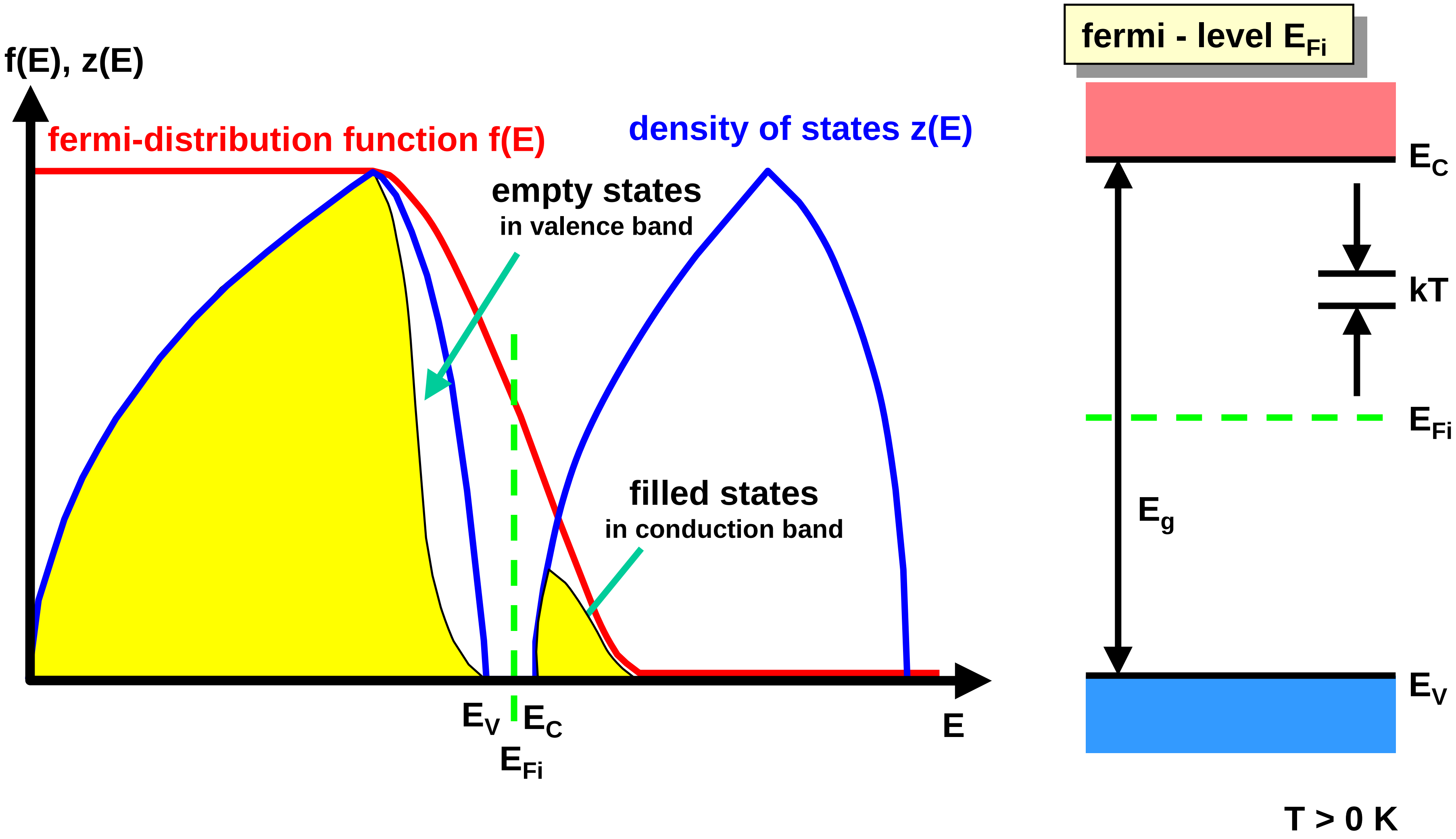
$$\mu_n = T^{-\beta_n}$$

$$\mu_p = T^{-\beta_p}$$

source: IWE

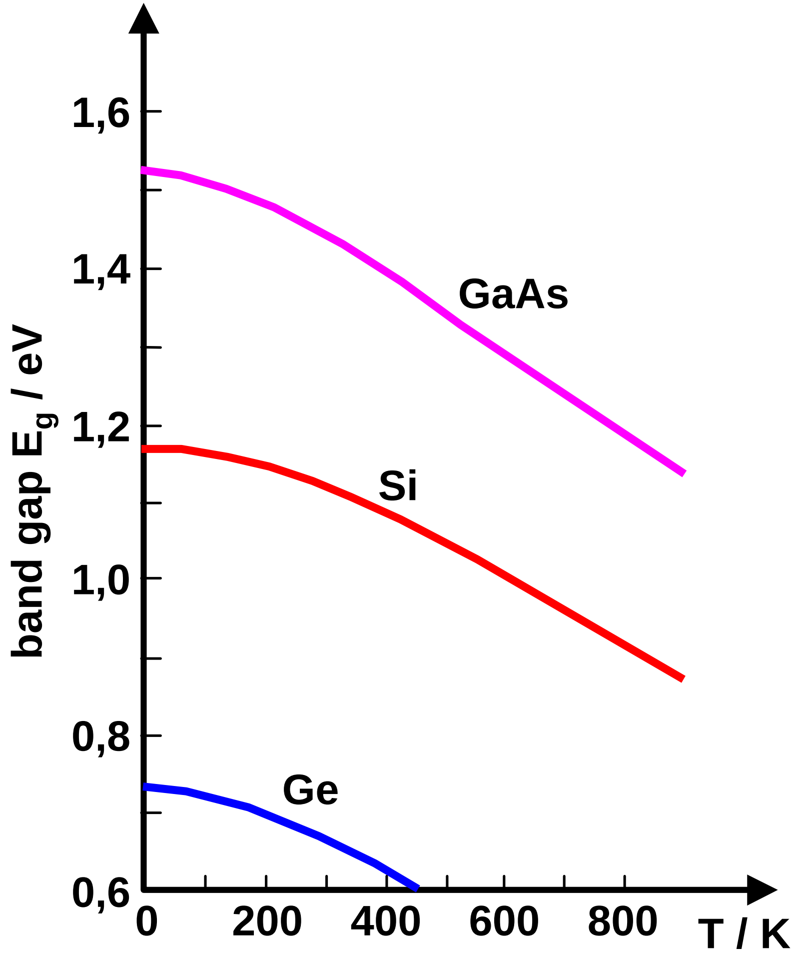
Semiconductors

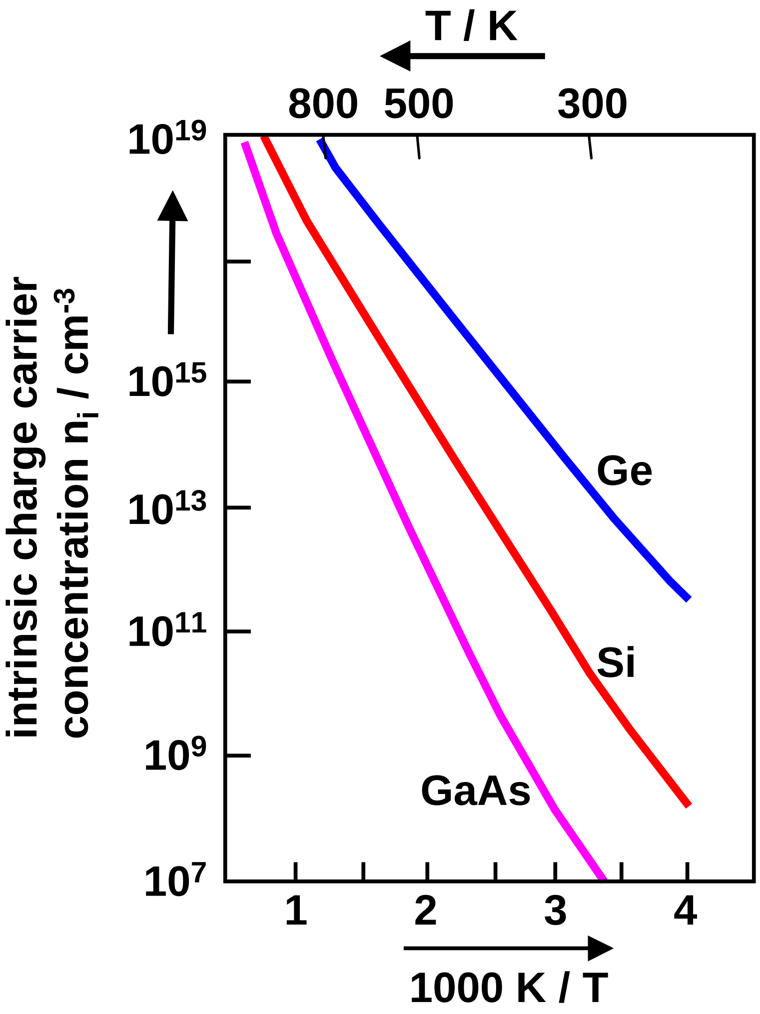
Fermi Distribution Function, Density of States and filled Electron States



source: [Heime / 3-40]

Semiconductors
Band Gap E_g and Concentration of Charge Carriers as f(T)

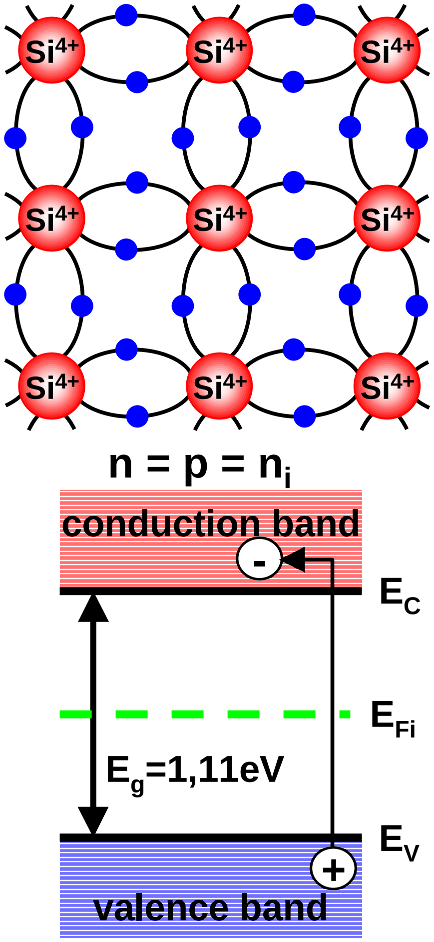




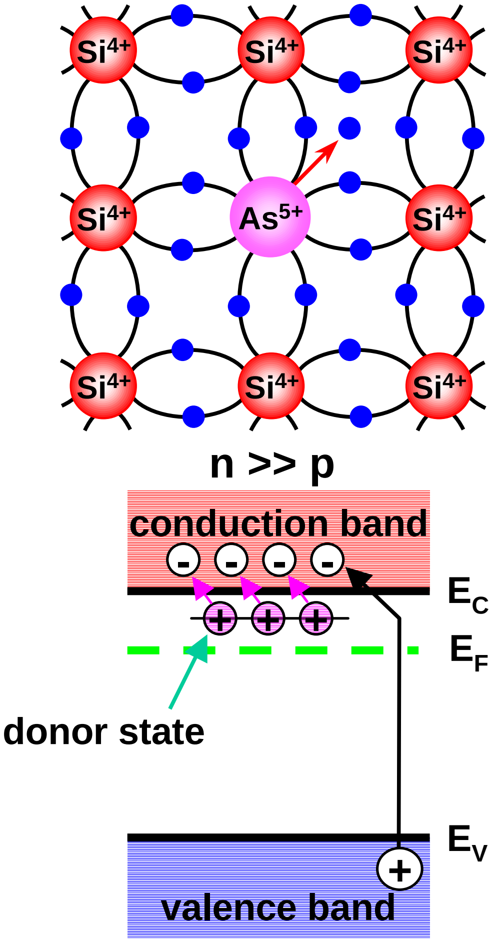
source: [Heime 3-25, 26]

Semiconductors
Intrinsic and Extrinsic (n- and p-Type) Semiconductors

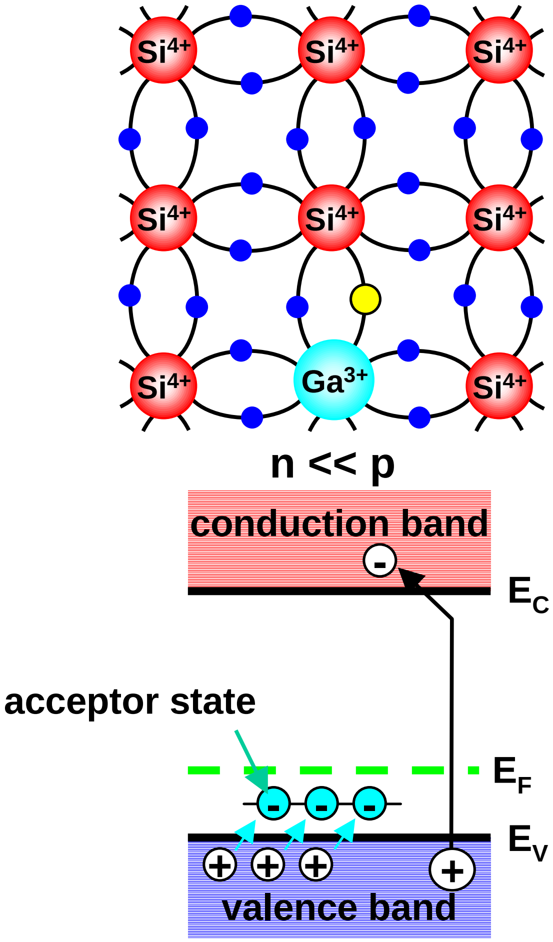
intrinsic semiconductor



extrinsic n-type (donor-doped)



extrinsic p-type (acceptor-doped)



source: [Hahn 73 / 98]

Semiconductors
Donors and Acceptors

donors

excitation from a donor state generates an electron in the conduction band

ionisation energy*:

$$\Delta E_D = \frac{m_n^* \cdot e_0^{\ 4}}{2 \cdot (4\pi \cdot \varepsilon_r \cdot \varepsilon_0 \cdot \hbar)^2}$$

in Si: P ΔE_D = 45 meV
Sb ΔE_D = 39 meV
As ΔE_D = 54 meV

acceptors

excitation from an acceptor state generates a hole in the valence band

ionisation energy*:

$$\Delta E_A = \frac{m_p^* \cdot e_0^{\ 4}}{2 \cdot (4\pi \cdot \varepsilon_r \cdot \varepsilon_0 \cdot \hbar)^2}$$

in Si: B ΔE_A = 45 meV
Al ΔE_A = 67 meV
Ga ΔE_A = 72 meV

*** calculation using the hydrogen model $H \rightarrow H^+ + e^- \Rightarrow$**

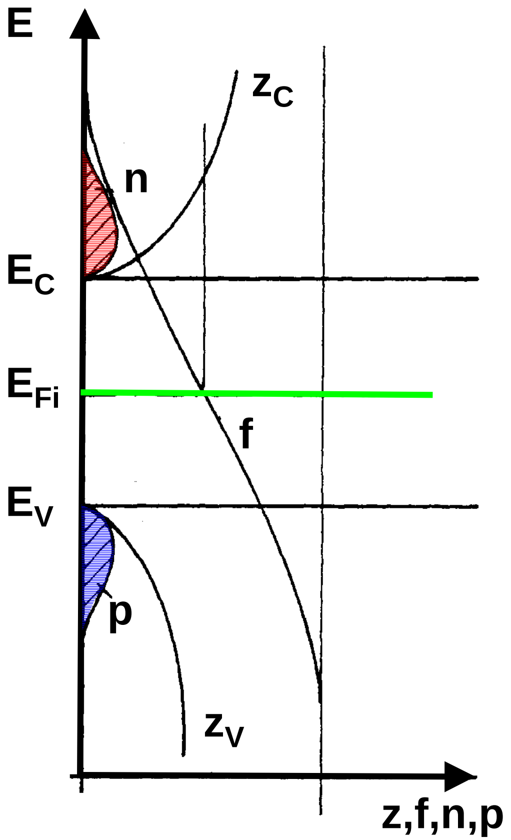
$$\Delta E_{Ion} = \frac{m_0 \cdot e_0^{\ 4}}{2 \cdot (4\pi \cdot \varepsilon_0 \cdot \hbar)^2} = 13{,}6 eV$$

source: IWE

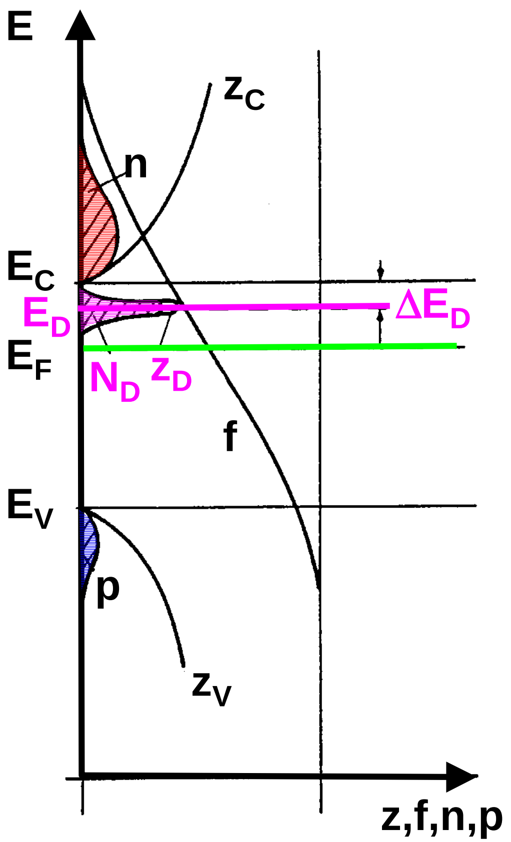
Semiconductors

Distribution Function f(E), Density of States z(E) and filled Electron States

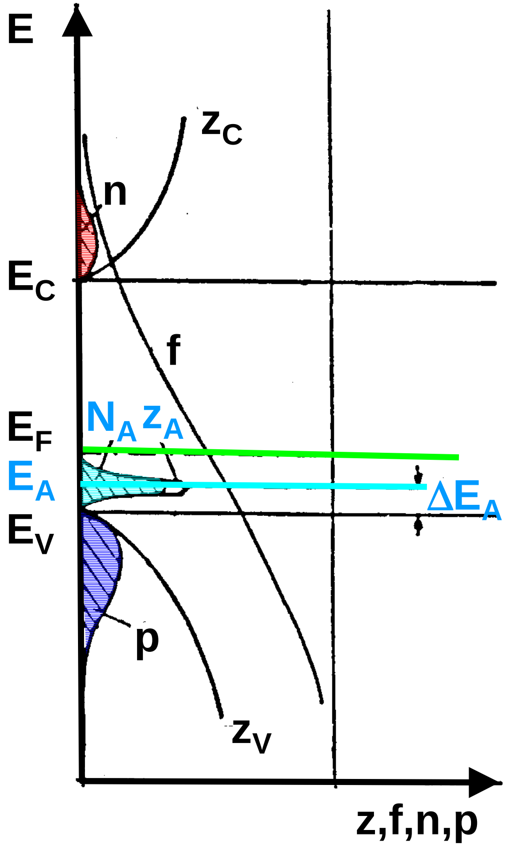
intrinsic
n = p



n-type (donor-doped)
n >> p

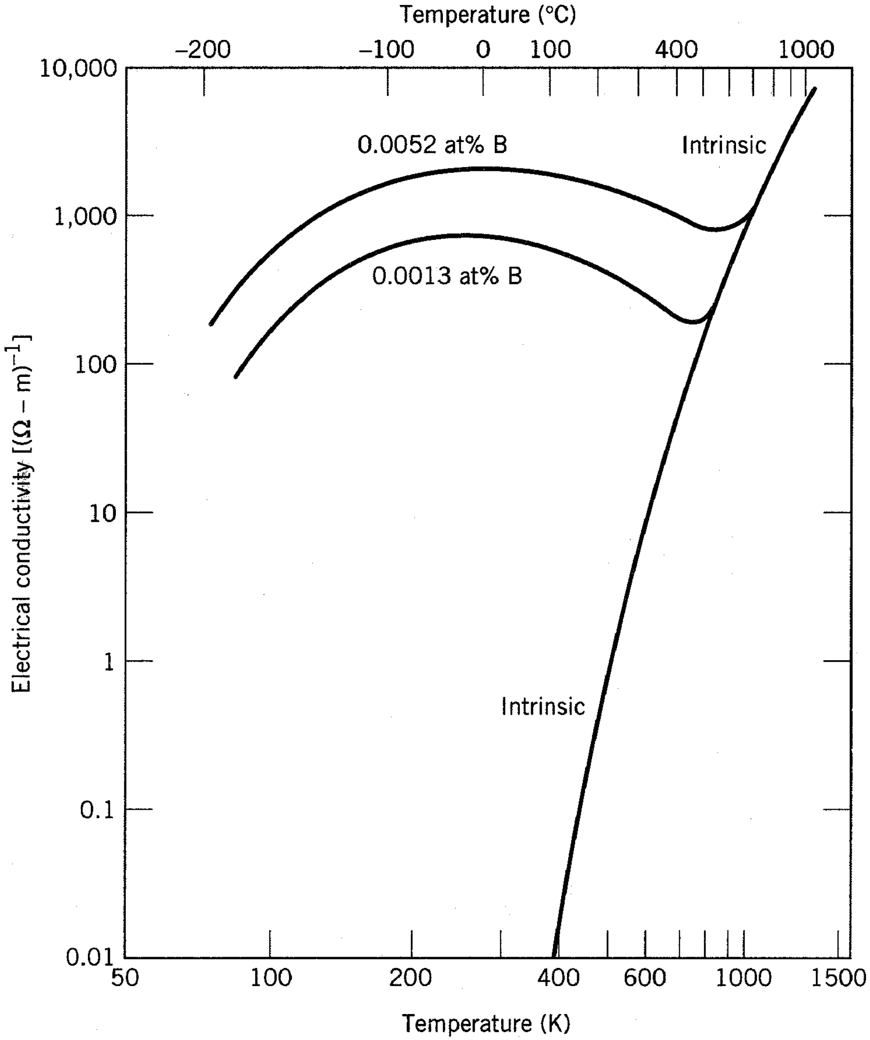


p-type (acceptor-doped)
p >> n



source: [Heime 3-77]

Semiconductors
Electrical Conductivity vs. Temperature

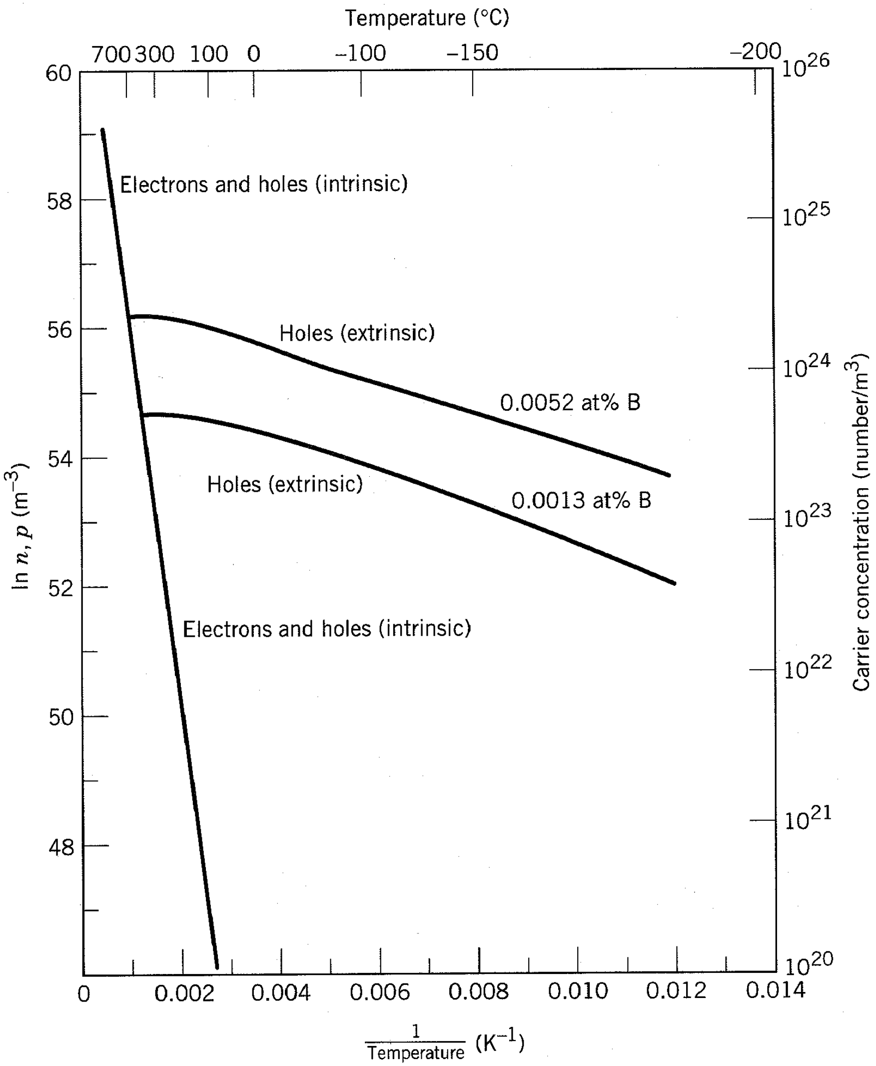


For intrinsic semiconduction:

$$\ln \sigma \cong C - \frac{E_g}{2kT}$$

C **- a temperature-independent constant**
E

Semiconductors
Charge Carrier Concentration vs. Reciprocal Temperature



For intrinsic semiconduction:

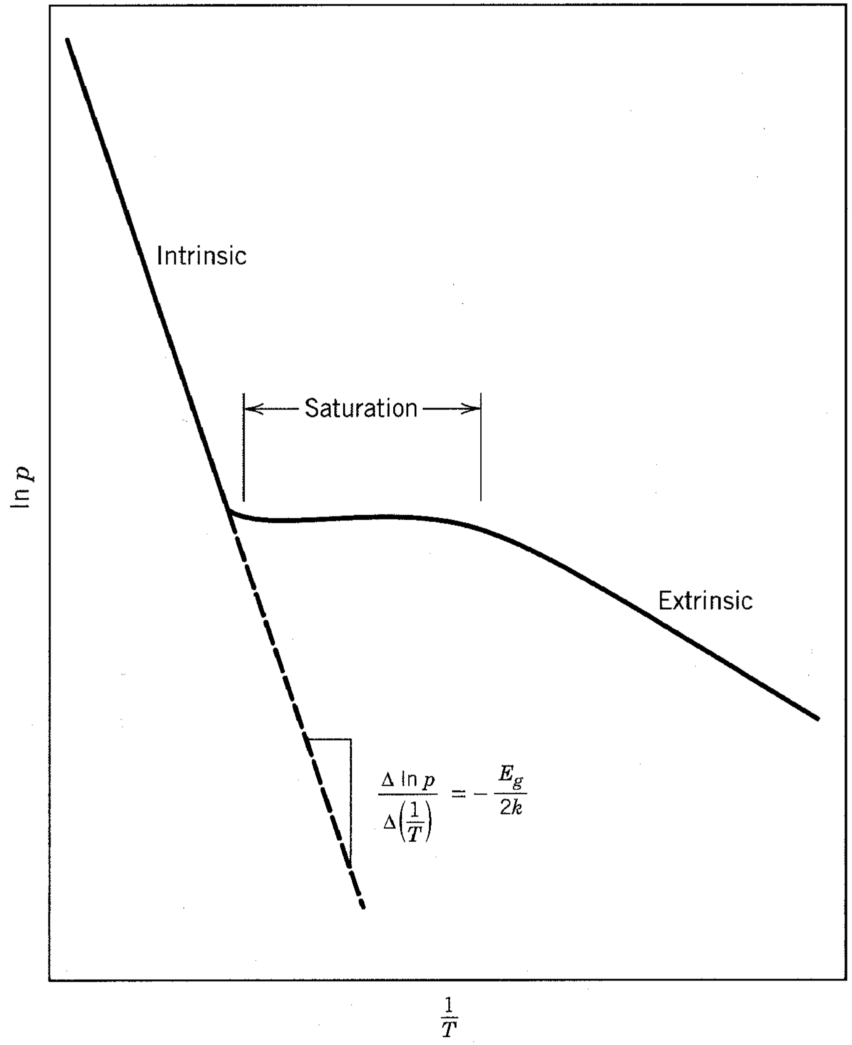
$$\ln n = \ln p \cong C' - \frac{E_g}{2kT}$$

$$E_g = -2k\left(\frac{\Delta \ln p}{\Delta(1/T)}\right) = 2k\left(\frac{\Delta \ln n}{\Delta(1/T)}\right)$$

source: [Cal 99 / 625]

Semiconductors

Extrinsic, Saturation and Intrinsic Behavior vs. Reciprocal Temperature



p-type extrinsic semiconductor

source: [Cal 99 / 626]

Semiconductors
Intrinsic and Extrinsic Conduction

- **intrinsic conductivity (n = p = n_i)**

$$\sigma_i = n_i \cdot e_0 \cdot (\mu_n + \mu_p) = n \cdot e_0 \cdot (\mu_n + \mu_p) = p \cdot e_0 \cdot (\mu_n + \mu_p)$$

- **n-type intrinsic conductivity (n >> p, n·p = n_i^2)**

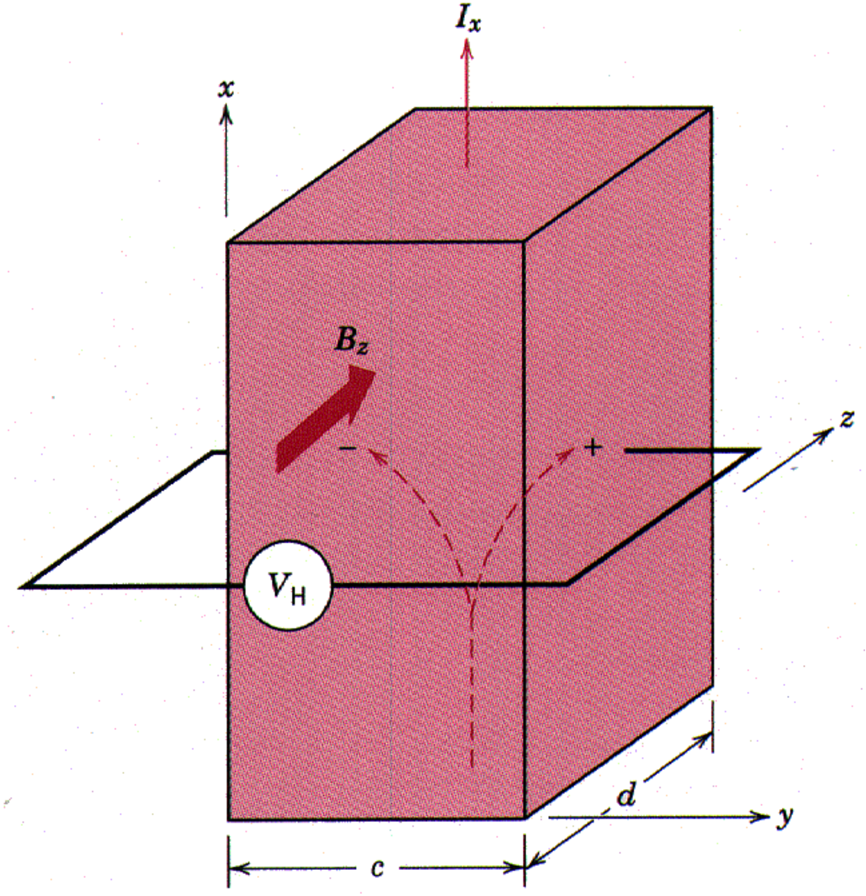
$$\sigma \cong n \cdot e_0 \cdot \mu_n$$

- **p-type intrinsic conductivity (n << p, n·p = n_i^2)**

$$\sigma \cong p \cdot e_0 \cdot \mu_p$$

source: IWE

Semiconductors
Hall Effect Experiment



V_H: Hall voltage, depends on:

I_x: current

B_z: magnetic field

d: the specimen thickness

$$V_H = \frac{R_H \cdot I_x \cdot B_z}{d}$$

R_H: Hall coefficient (constant for a given material)

$R_H = 1/ne_0$, $\mu_n = |R_H| \cdot \sigma$, (n-type)

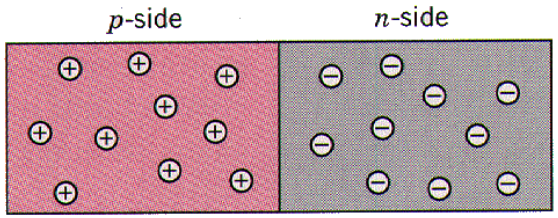
$R_H = -1/pe_0$, $\mu_p = |R_H| \cdot \sigma$, (p-type)

Determination of majority charge carrier type, concentration and mobility

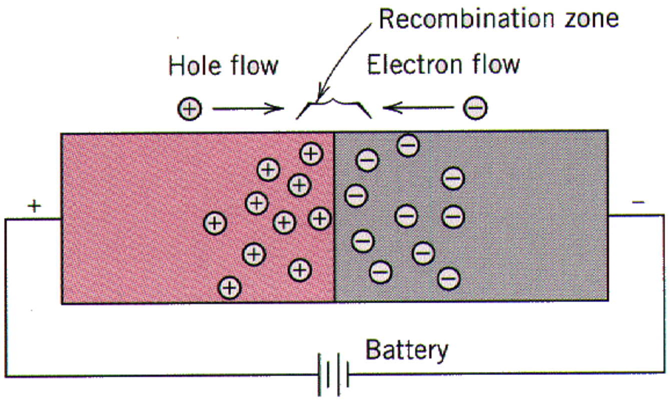
source: [Cal 99 / 629]

Semiconductors: Devices
p-n Rectifying Junction

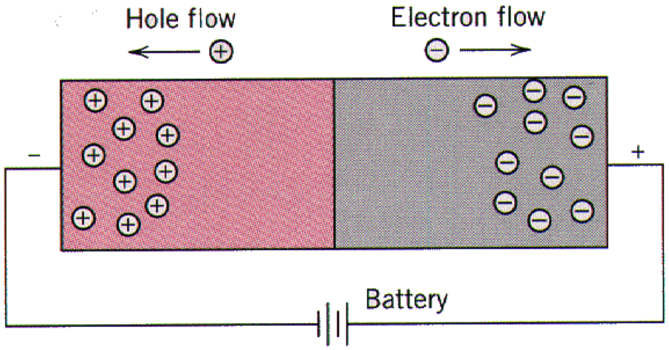
electron /hole distribution for:



no electrical potential



forward bias

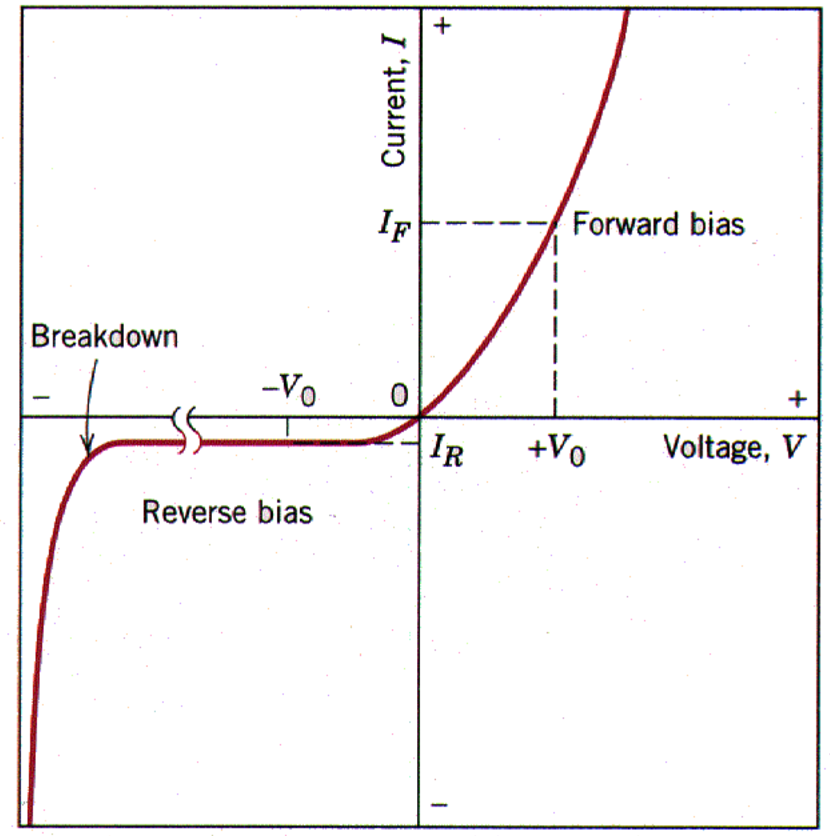


reverse bias

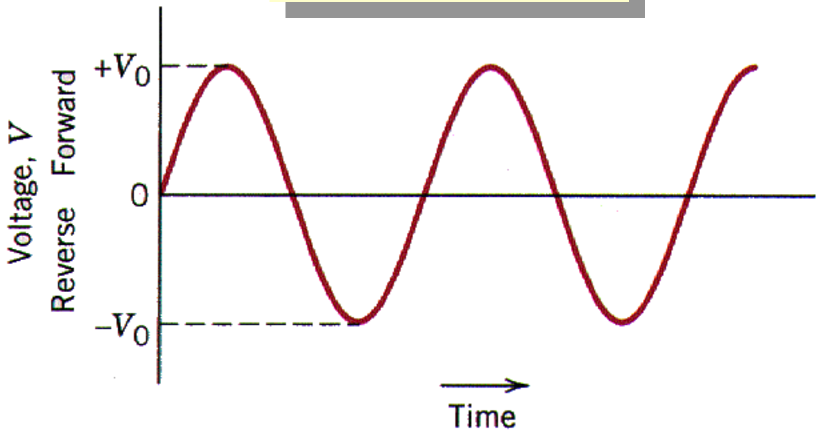
source: [Cal 99 / 631]

Semiconductors: Devices
p-n Rectifying Junction

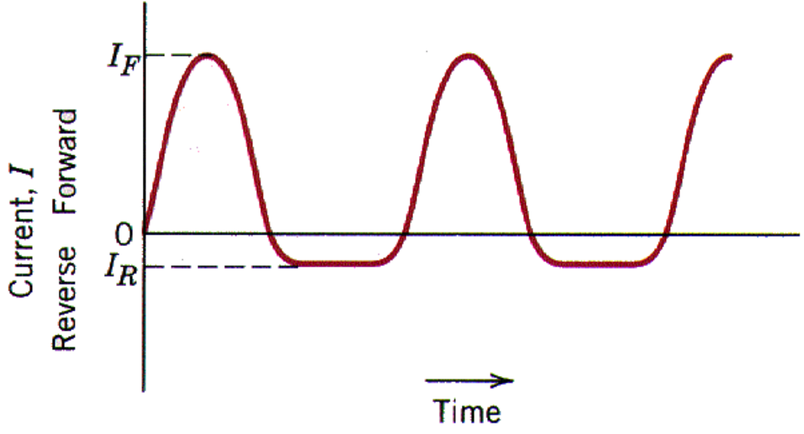
current - voltage characteristics



voltage vs. time



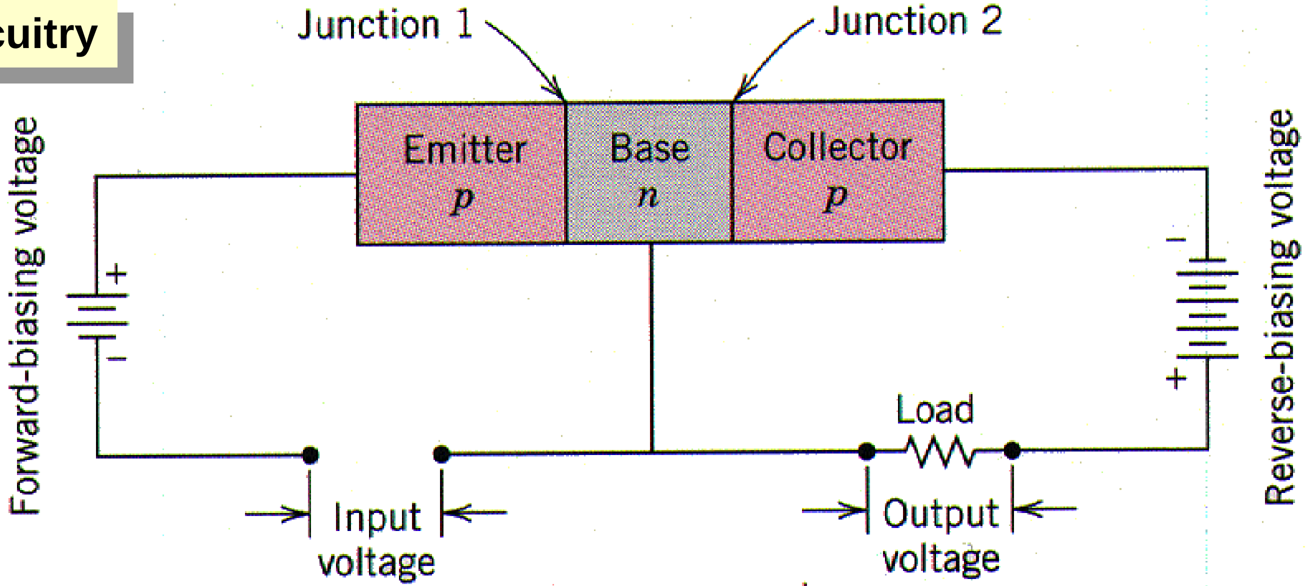
current vs. time



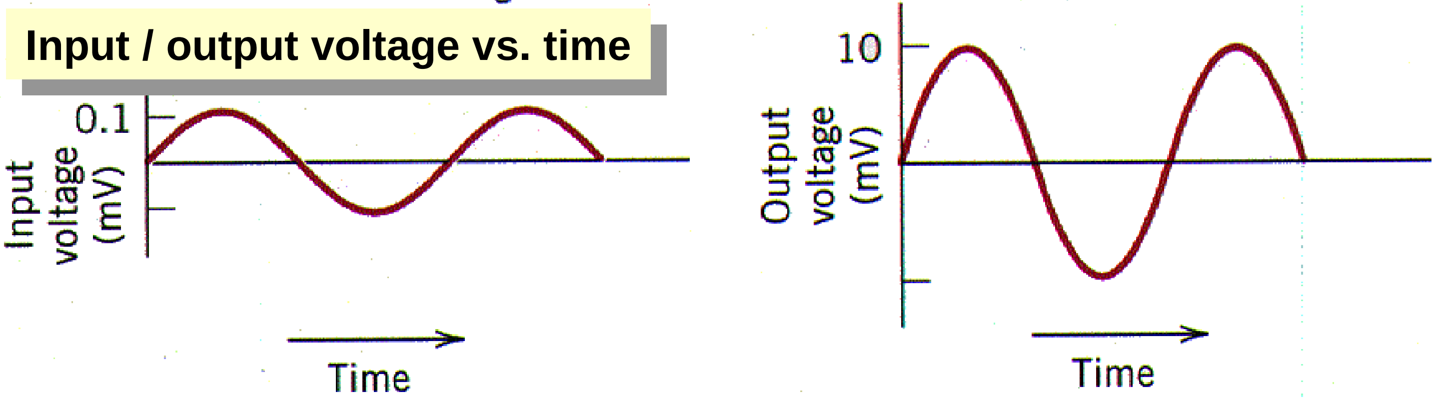
source: [Cal 99 / 632]

Semiconductors: Devices
p-n-p Junction Transistor

circuitry



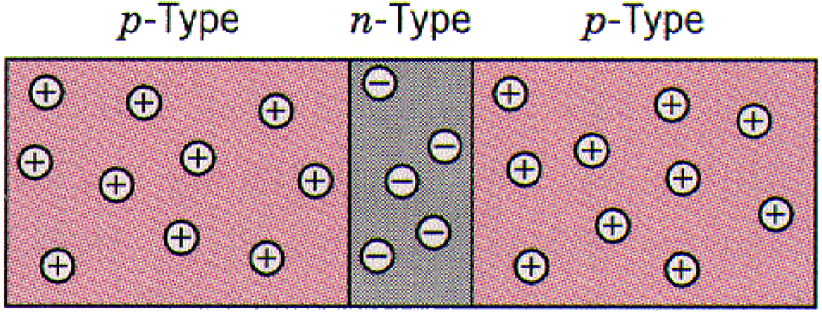
Input / output voltage vs. time



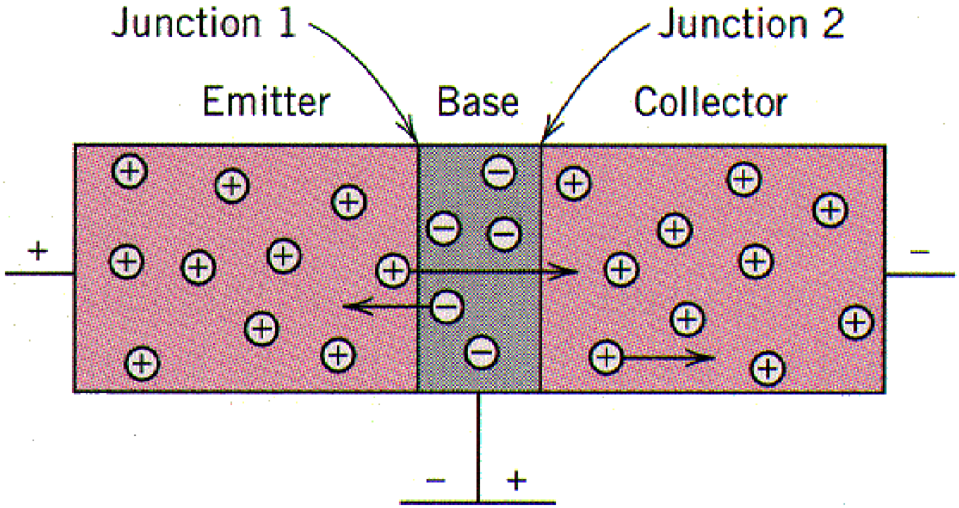
source: [Cal 99 / 633]

Semiconductors: Devices
p-n-p Junction Transistor

no potential applied

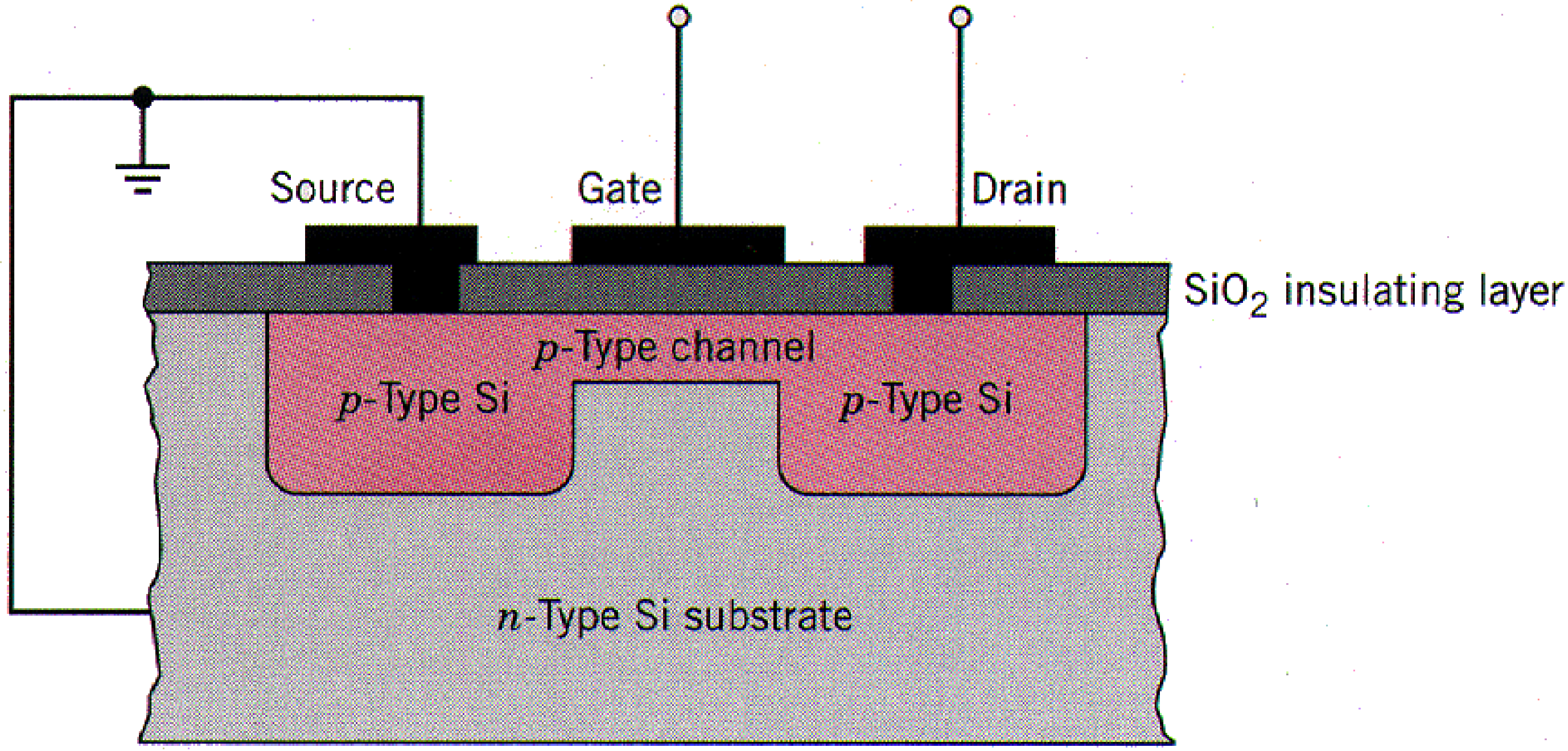


bias applied



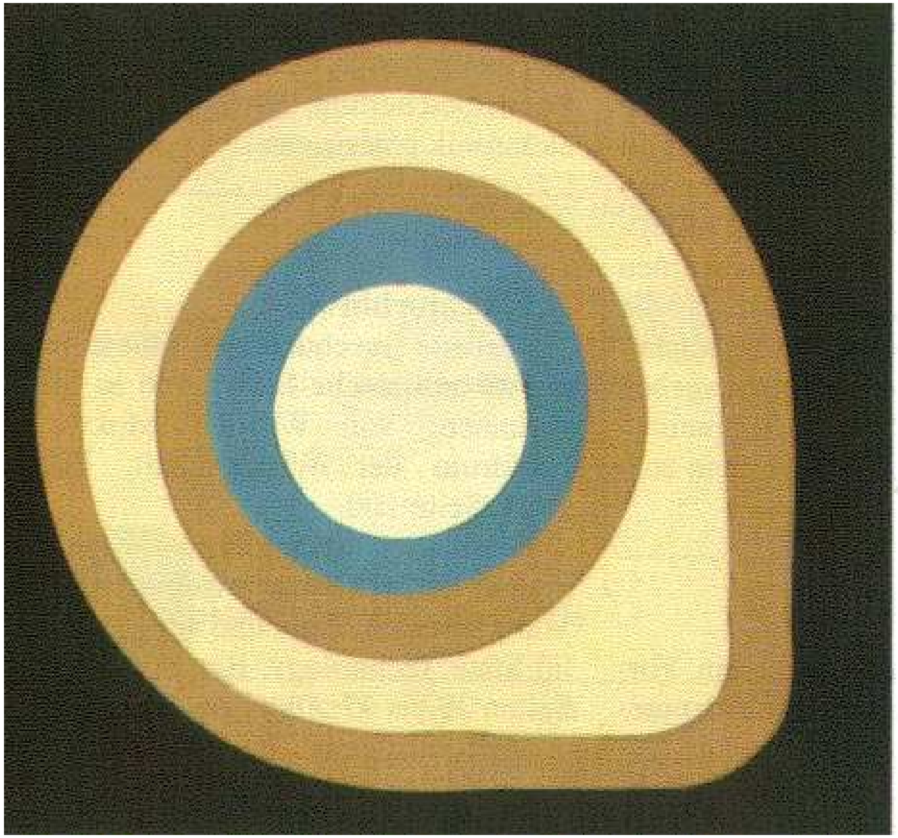
source: [Cal 99 / 634]

Semiconductors: Devices
MOSFET-Transistor

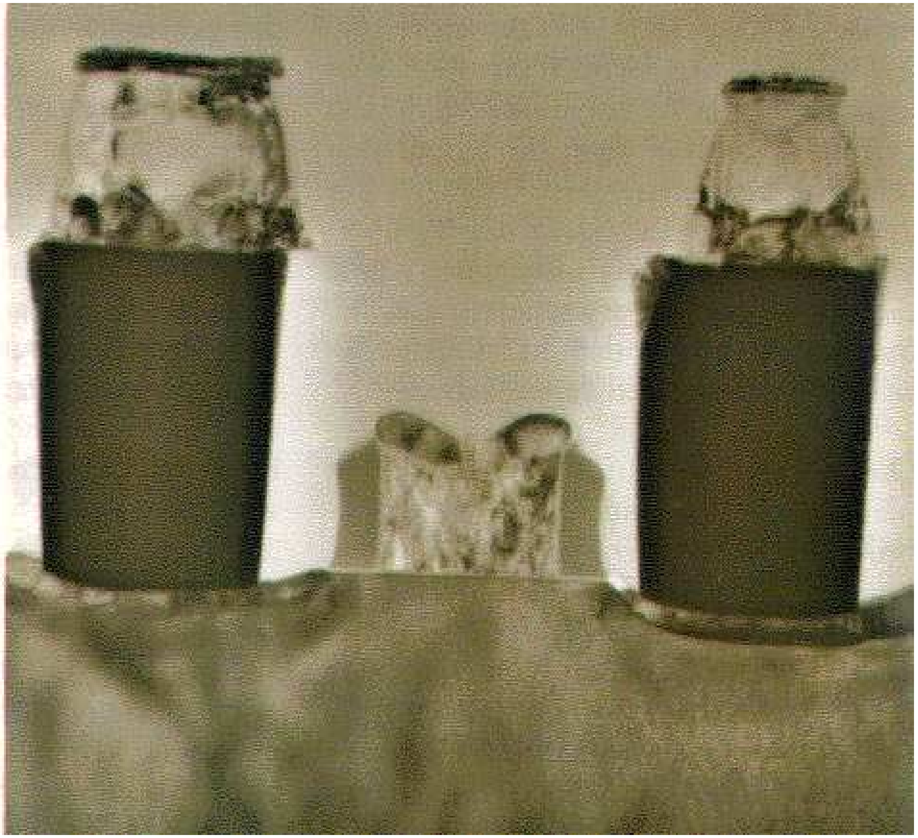


source: [Cal 99 / 634]

Semiconductors
Development of Microelectronics



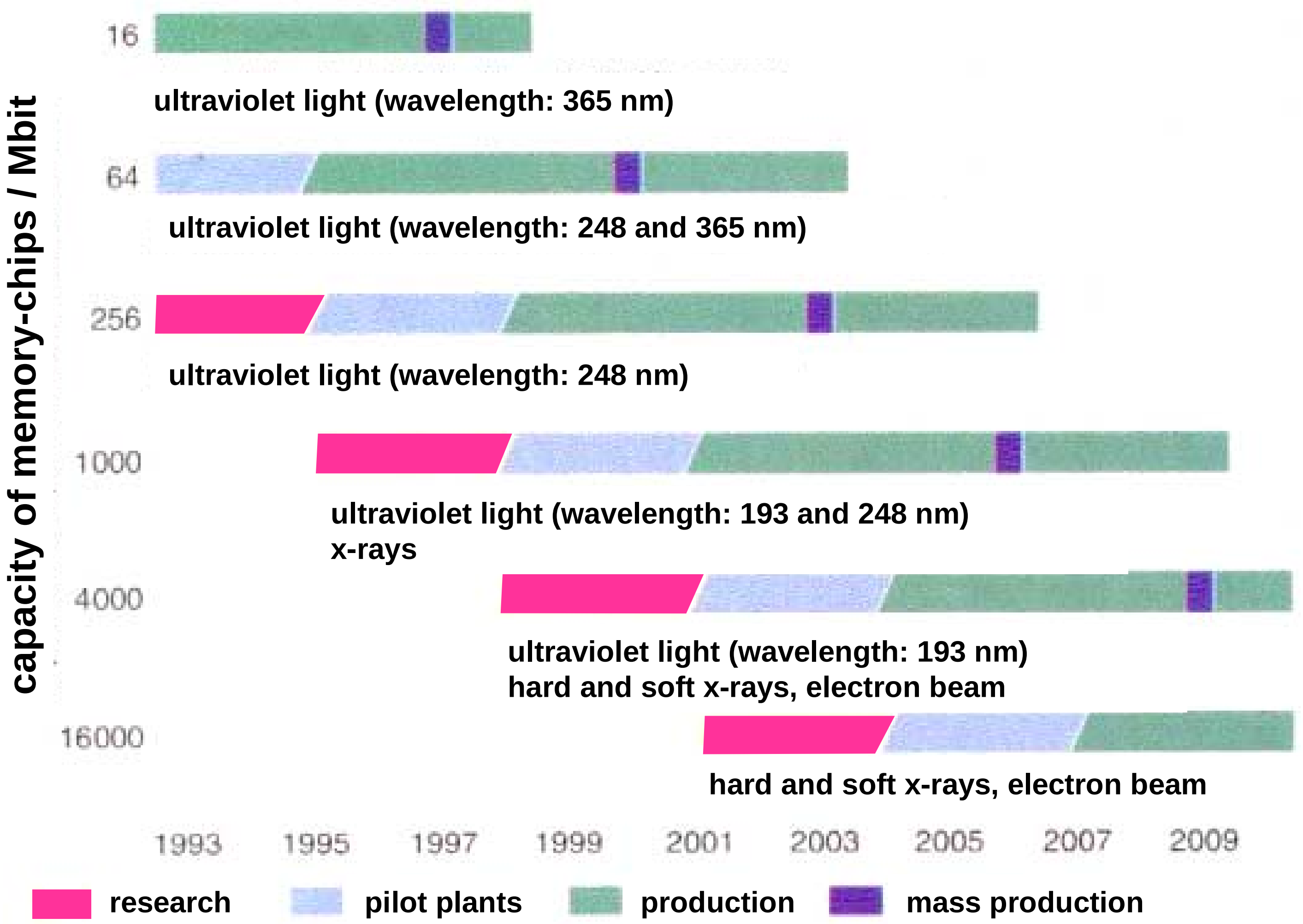
1959: 1^{st} planar transistor
∅ 764 µm



1995: transistor structures
between 0,4 and 1,3 µm

source: [Spekd4 / 52]

Semiconductors
Development of Lithography Technology



ultraviolet light (wavelength: 365 nm)

ultraviolet light (wavelength: 248 and 365 nm)

ultraviolet light (wavelength: 248 nm)

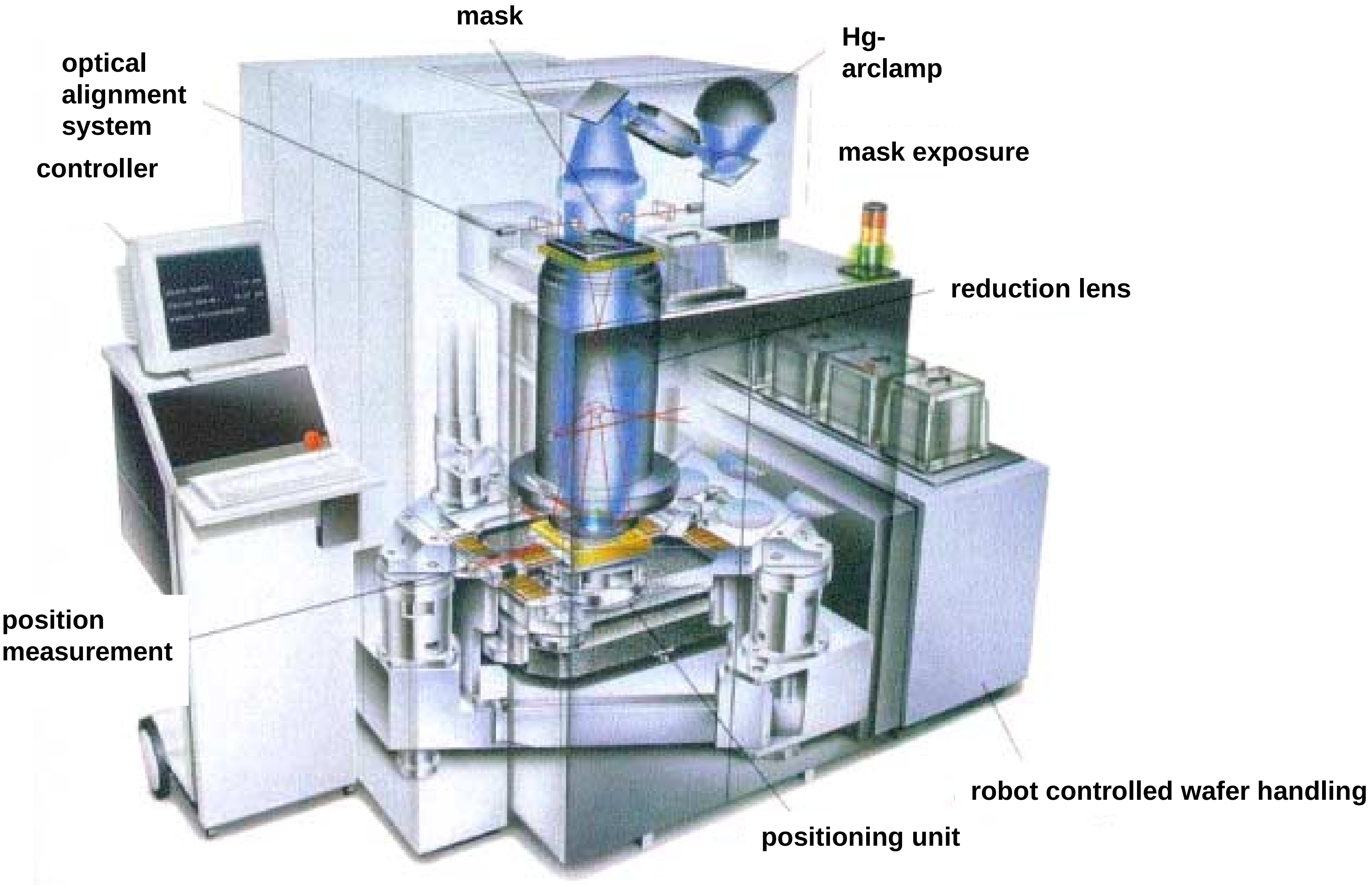
ultraviolet light (wavelength: 193 and 248 nm)
x-rays

ultraviolet light (wavelength: 193 nm)
hard and soft x-rays, electron beam

hard and soft x-rays, electron beam

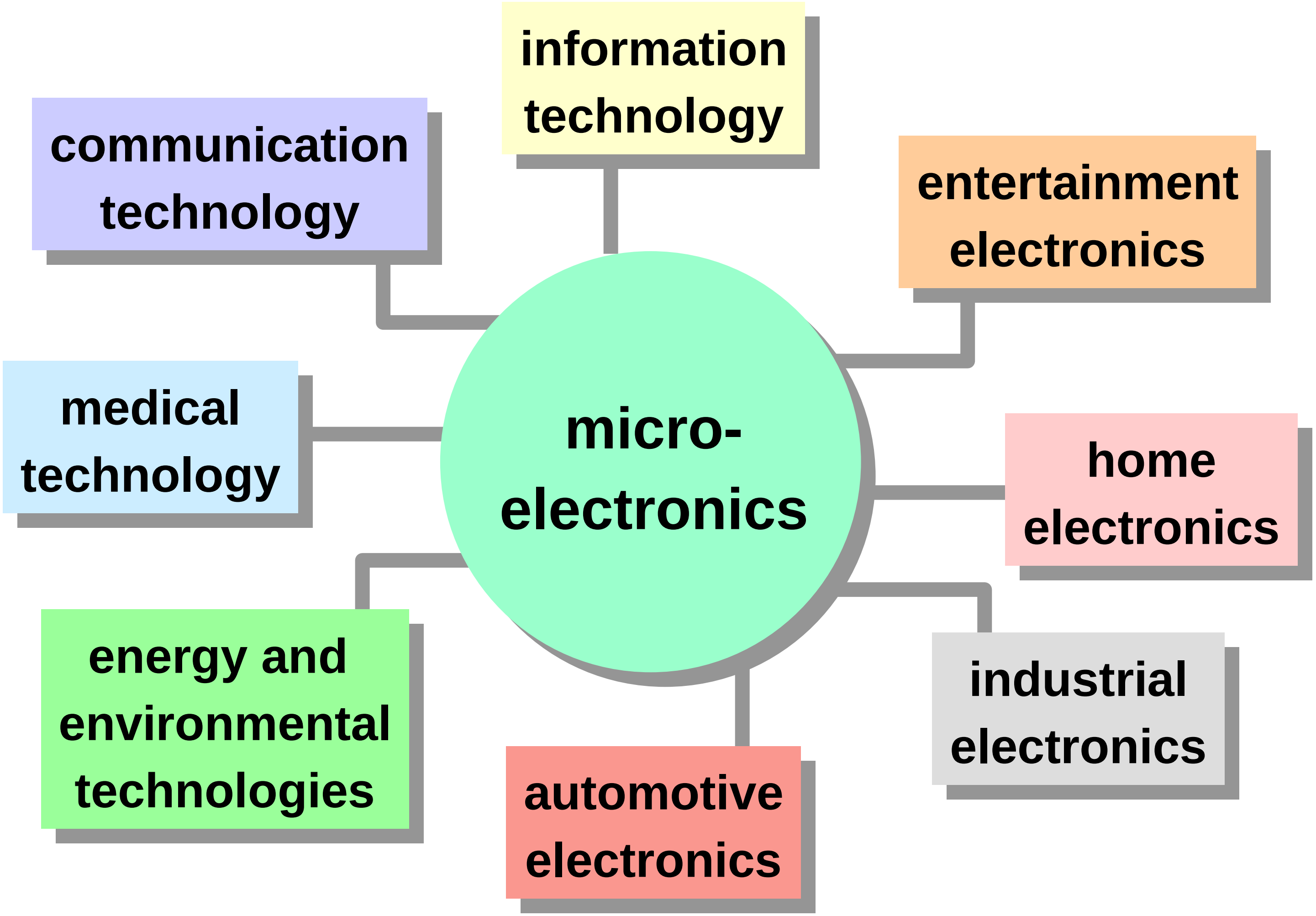
source: [Spekd4 / 53]

Semiconductors
Photolithography System



source: [Spekd4 / 55]

Semiconductors



micro-electronics

information technology

communication technology

entertainment electronics

medical technology

home electronics

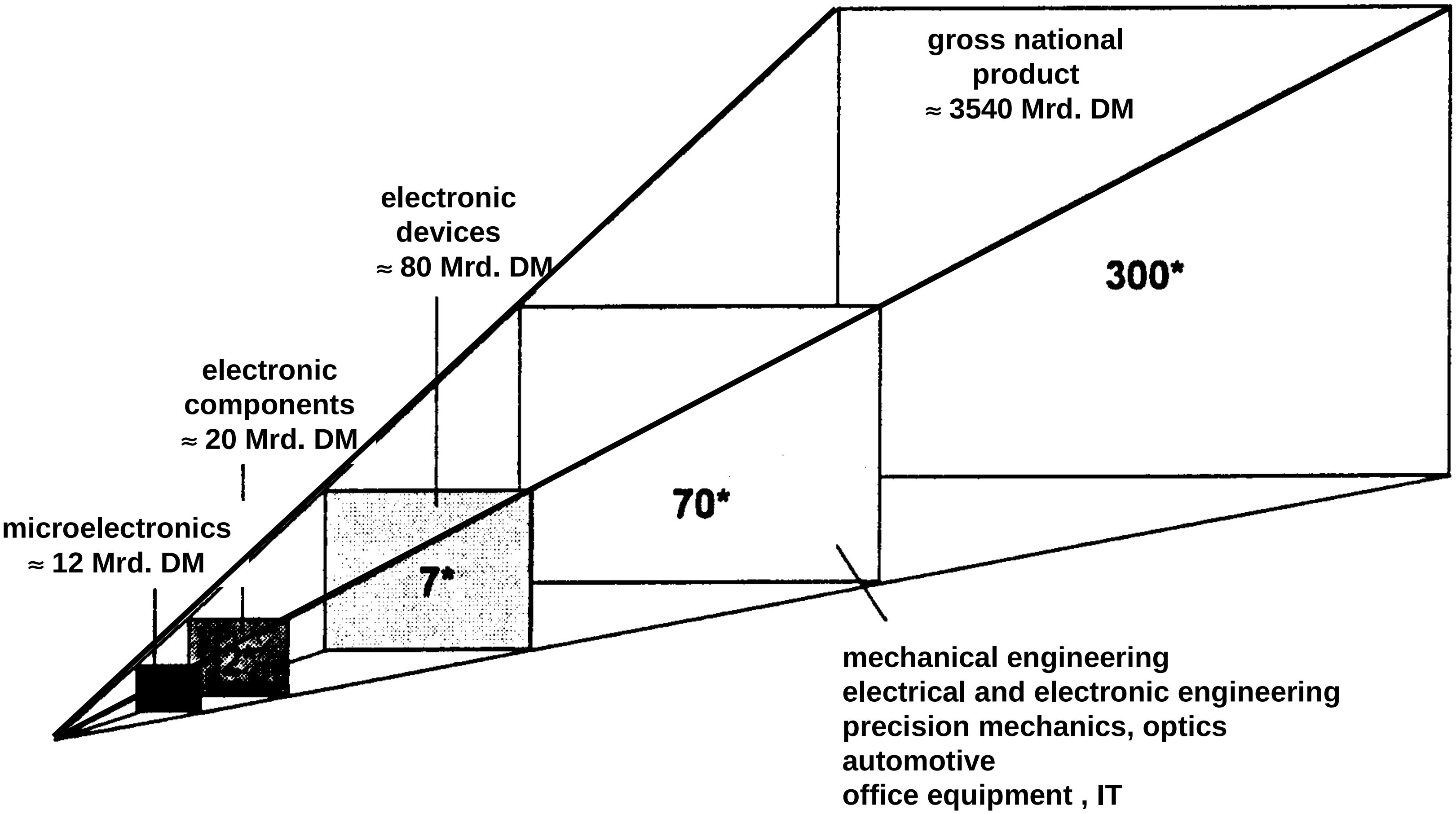
energy and environmental technologies

automotive electronics

industrial electronics

source: Siemens

Semiconductors
Sales 1996



gross national product ≈ 3540 Mrd. DM

electronic devices ≈ 80 Mrd. DM

electronic components ≈ 20 Mrd. DM

microelectronics ≈ 12 Mrd. DM

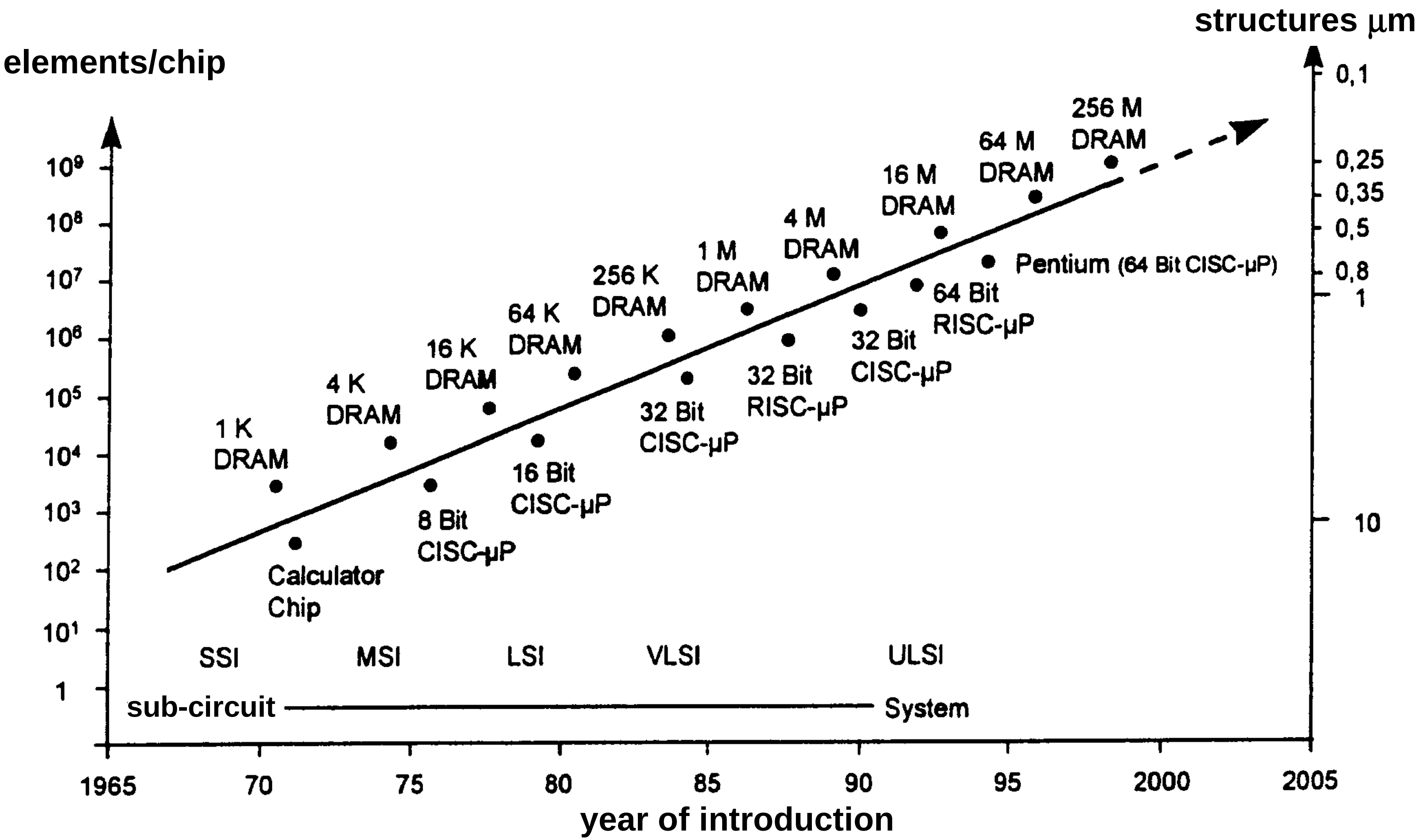
mechanical engineering
electrical and electronic engineering
precision mechanics, optics
automotive
office equipment , IT

***compared to microelectronics**

Quelle: GMM

source: Siemens

Semiconductors
Developement of Integration



source: Siemens