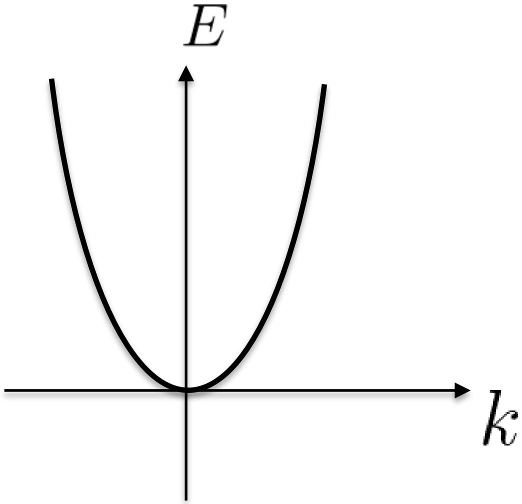
Revisando teoria de bandas

$U(\boldsymbol{r}) = 0$



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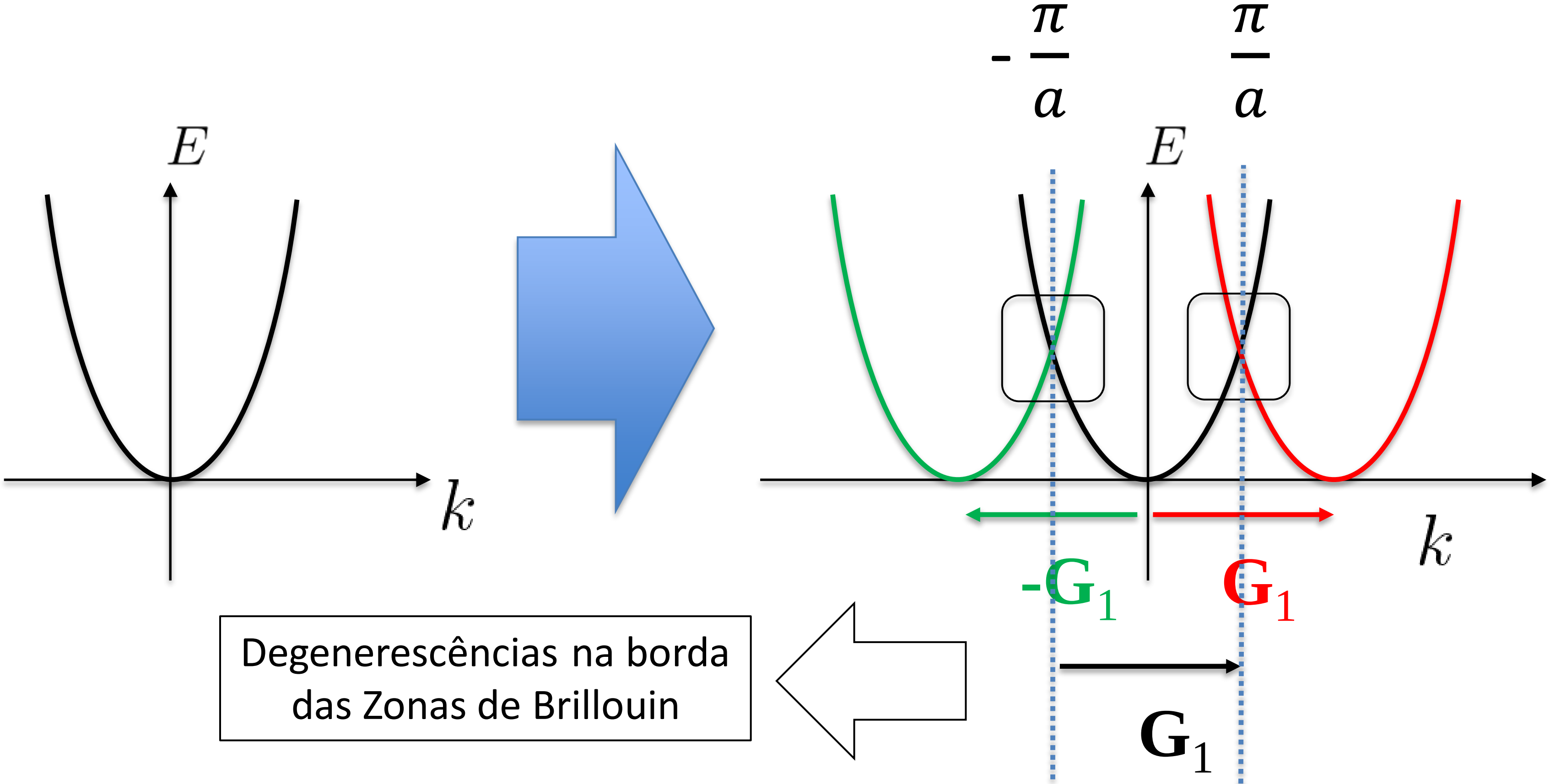

Revisando teoria de bandas

$$\begin{pmatrix} \langle \lambda_{\boldsymbol{k}-\boldsymbol{G}_j} | \widehat{H} | \lambda_{\boldsymbol{k}-\boldsymbol{G}_j} \rangle & \langle \lambda_{\boldsymbol{k}-\boldsymbol{G}_n} | \widehat{H} | \lambda_{\boldsymbol{k}-\boldsymbol{G}_j} \rangle \\ \langle \lambda_{\boldsymbol{k}-\boldsymbol{G}_j} | \widehat{H} | \lambda_{\boldsymbol{k}-\boldsymbol{G}_n} \rangle & \langle \lambda_{\boldsymbol{k}-\boldsymbol{G}_n} | \widehat{H} | \lambda_{\boldsymbol{k}-\boldsymbol{G}_n} \rangle \end{pmatrix} = \begin{pmatrix} \lambda_{\boldsymbol{k}-\boldsymbol{G}_j} & U_{\boldsymbol{G}_n-\boldsymbol{G}_j} \\ U_{\boldsymbol{G}_j-\boldsymbol{G}_n} & \lambda_{\boldsymbol{k}-\boldsymbol{G}_n} \end{pmatrix}$$

$$\lambda_{\boldsymbol{k}\,(j,n)\,\pm} = \frac{1}{2}\left(\lambda_{\boldsymbol{k}-\boldsymbol{G}_j} + \lambda_{\boldsymbol{k}-\boldsymbol{G}_n}\right) + \frac{1}{2}\sqrt{\left(\lambda_{\boldsymbol{k}-\boldsymbol{G}_j} - \lambda_{\boldsymbol{k}-\boldsymbol{G}_n}\right)^2 + U^2_{\boldsymbol{G}_j-\boldsymbol{G}_n}}$$

Revisando teoria de bandas

$$\begin{pmatrix} \langle \lambda_{\boldsymbol{k}-\boldsymbol{G}_j} | \hat{H} | \lambda_{\boldsymbol{k}-\boldsymbol{G}_j} \rangle & \langle \lambda_{\boldsymbol{k}-\boldsymbol{G}_n} | \hat{H} | \lambda_{\boldsymbol{k}-\boldsymbol{G}_j} \rangle \\ \langle \lambda_{\boldsymbol{k}-\boldsymbol{G}_j} | \hat{H} | \lambda_{\boldsymbol{k}-\boldsymbol{G}_n} \rangle & \langle \lambda_{\boldsymbol{k}-\boldsymbol{G}_n} | \hat{H} | \lambda_{\boldsymbol{k}-\boldsymbol{G}_n} \rangle \end{pmatrix} = \begin{pmatrix} \lambda_{\boldsymbol{k}-\boldsymbol{G}_j} & U_{\boldsymbol{G}_n-\boldsymbol{G}_j} \\ U_{\boldsymbol{G}_j-\boldsymbol{G}_n} & \lambda_{\boldsymbol{k}-\boldsymbol{G}_n} \end{pmatrix}$$

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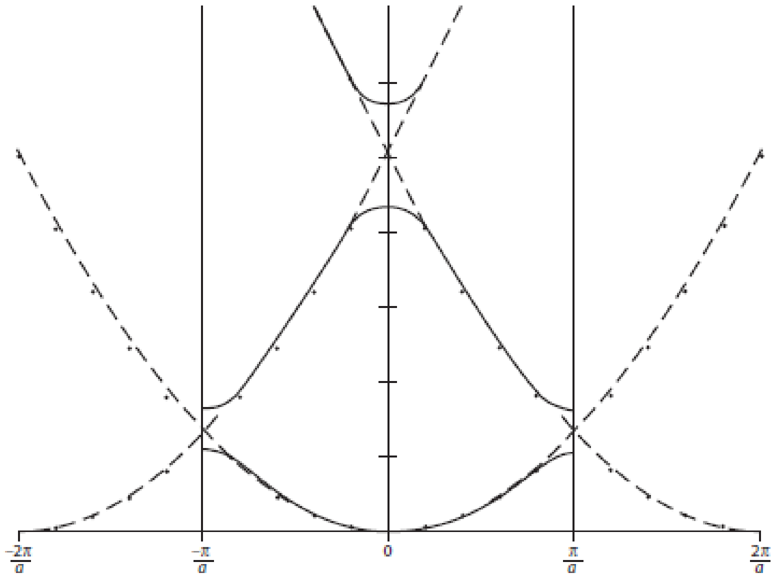

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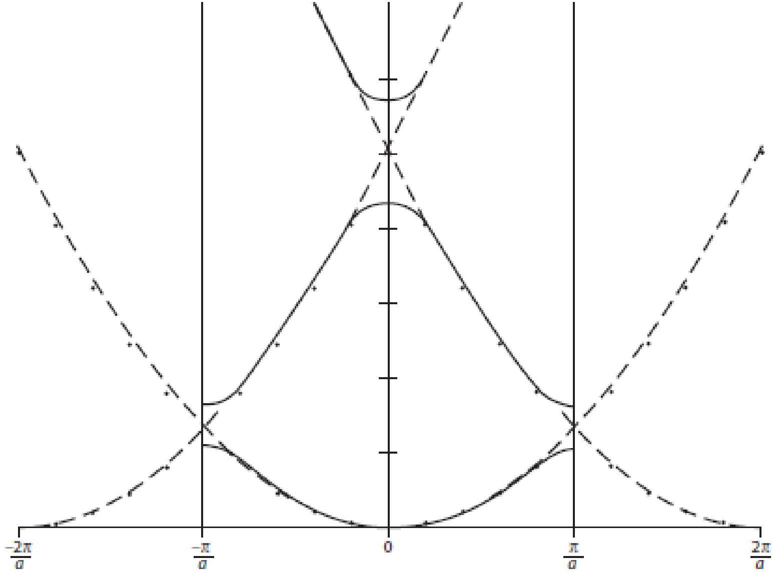

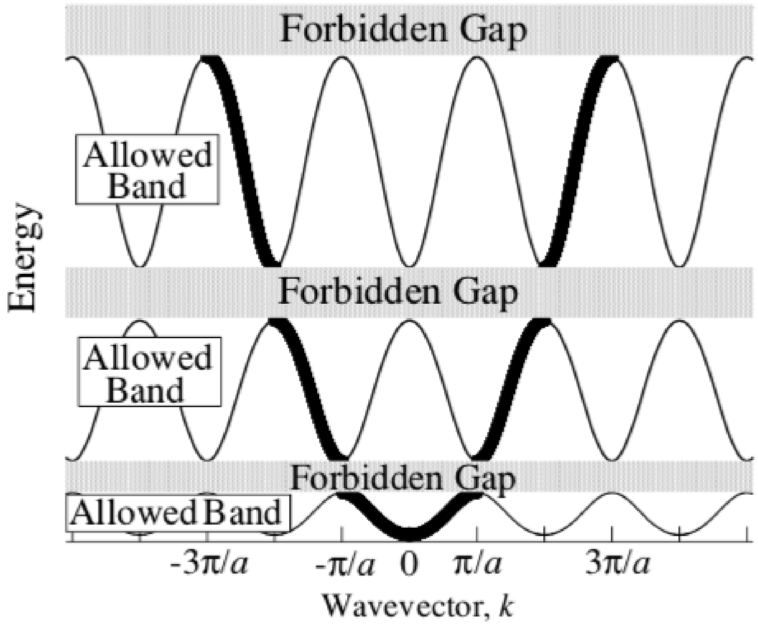

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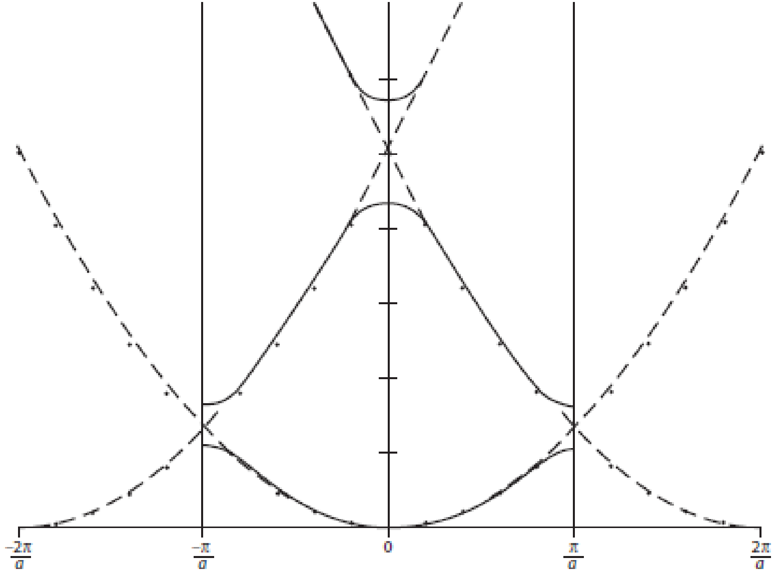

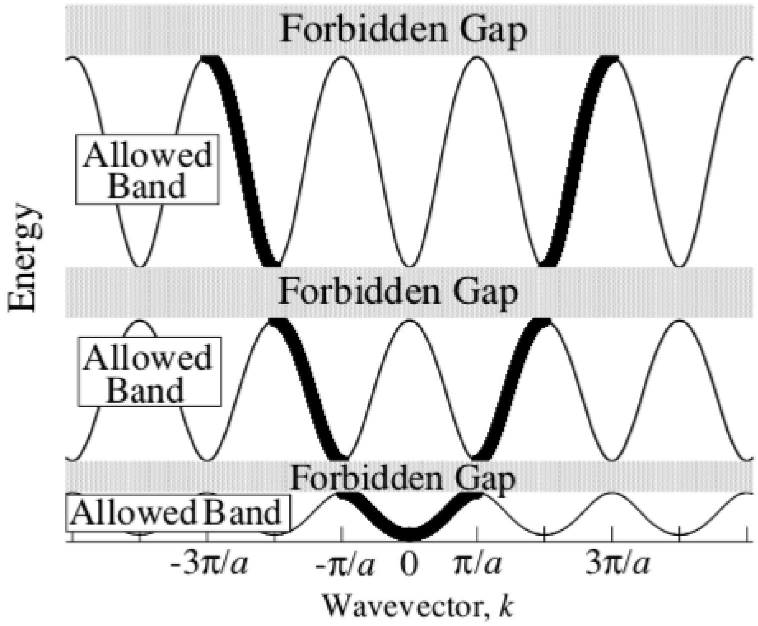

$$\sigma(T) \propto e^{-\Delta E / k_B T}$$

Semicondutores

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W. Pauli (1931): "*One shouldn't work on semiconductors, that is a filthy mess; who knows whether any semiconductors exist!*"

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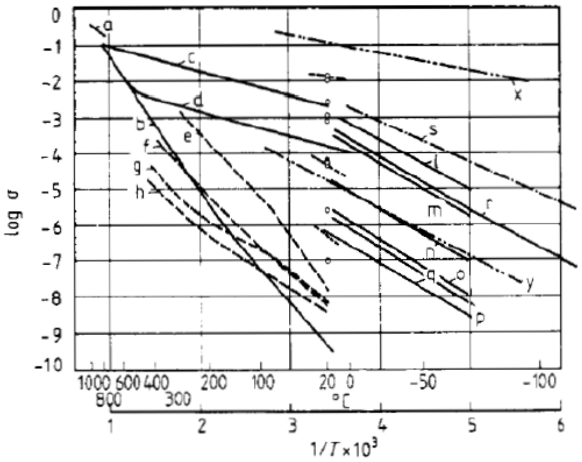

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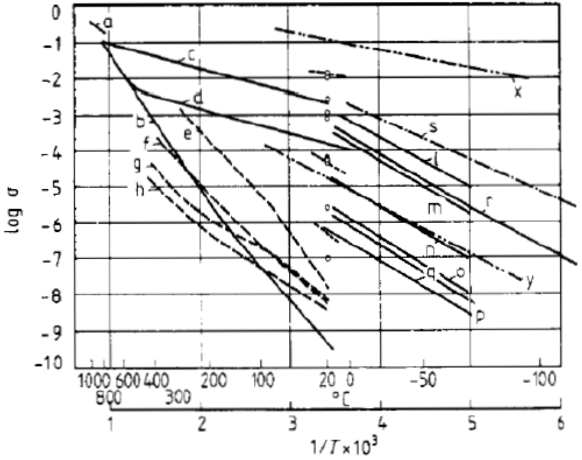
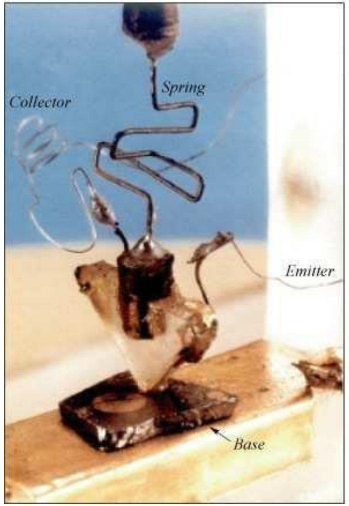
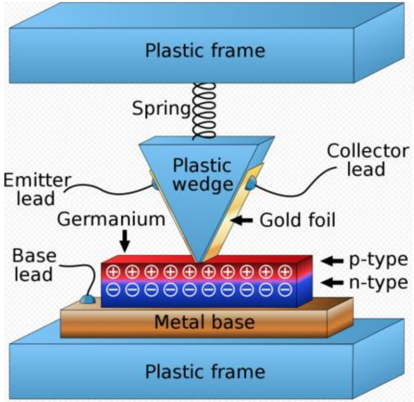
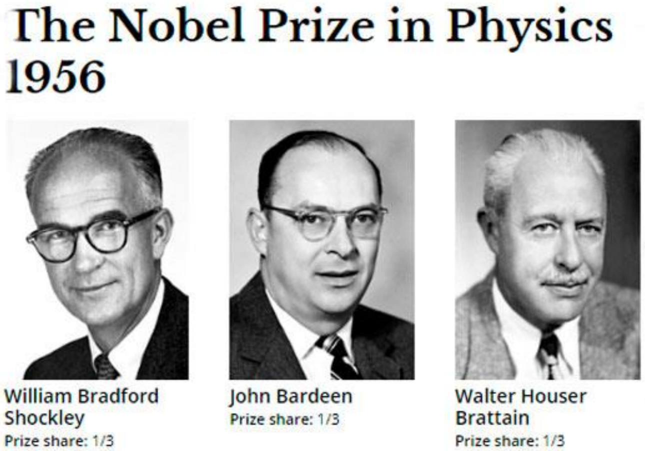


O primeiro transistor foi criado em 1947, no Bell’s Lab.







Semicondutores

Primeiro circuito integrado: 1958

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Nobel Prize in Physics (2000)

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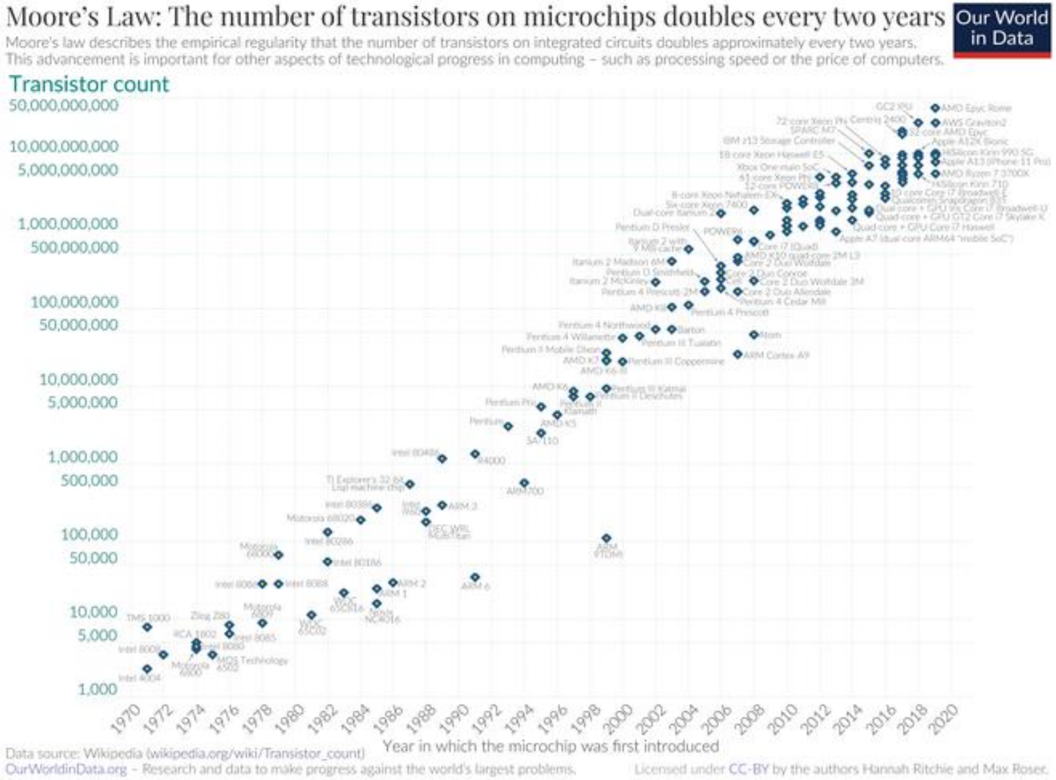

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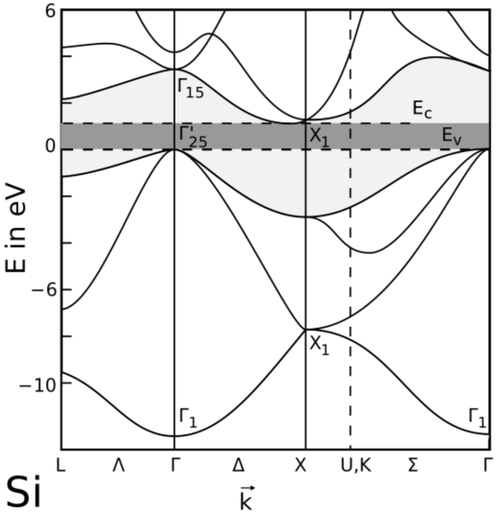
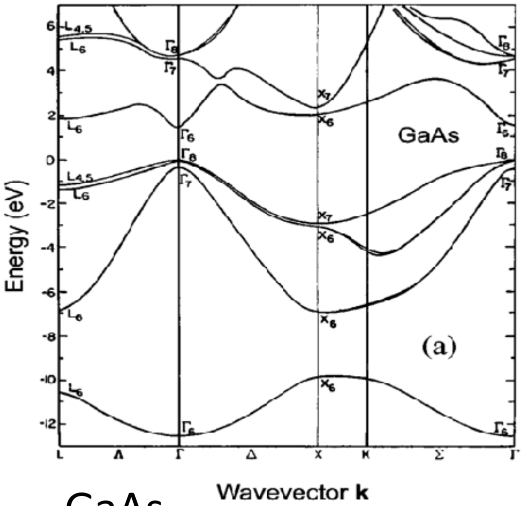
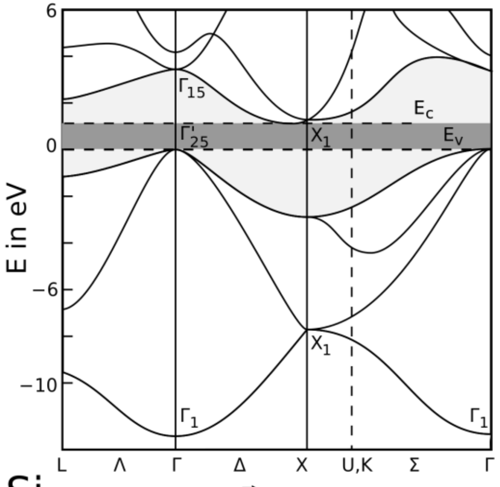


Si

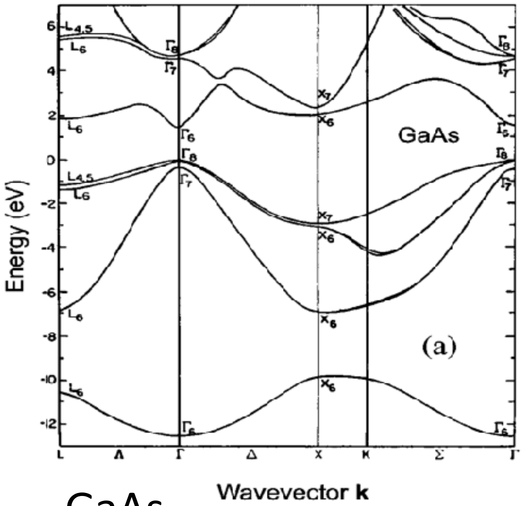


GaAs

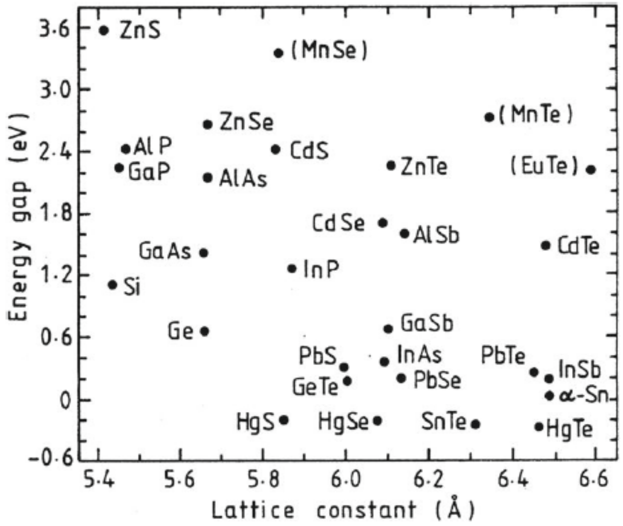
Semicondutores



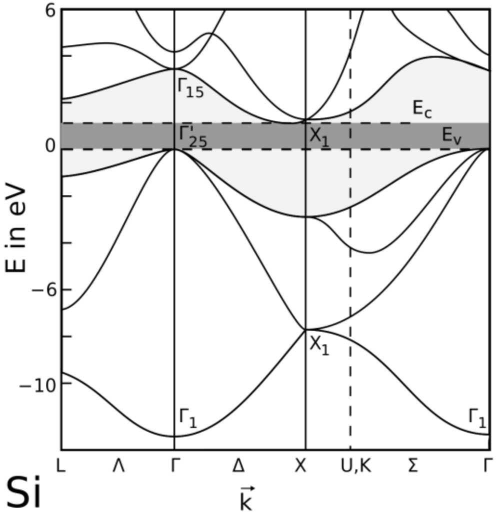
Si



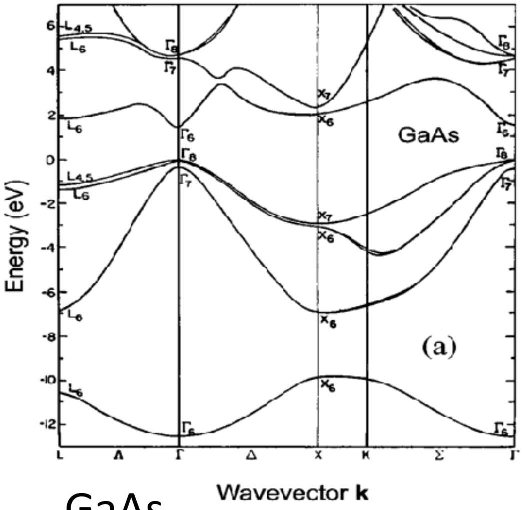
GaAs



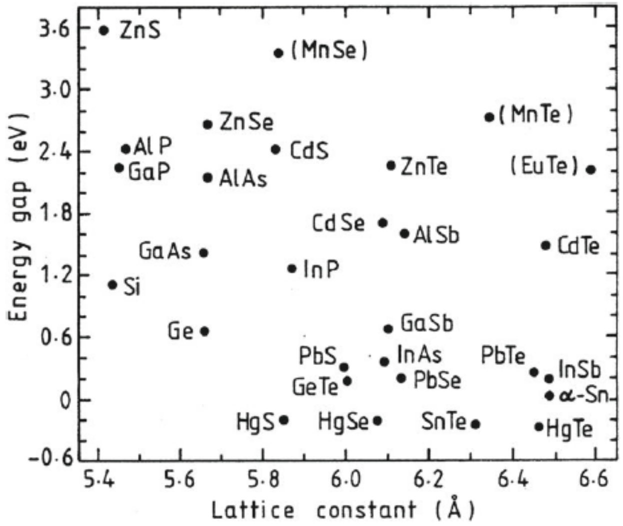
Semicondutores



Si



GaAs



Gap direto ou indireto?

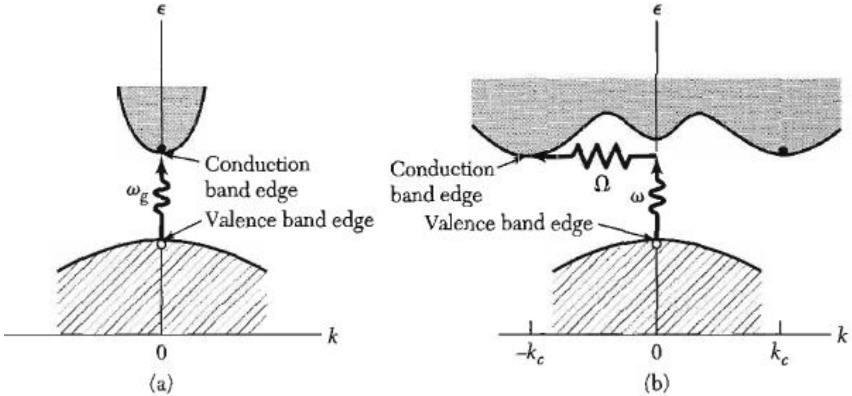


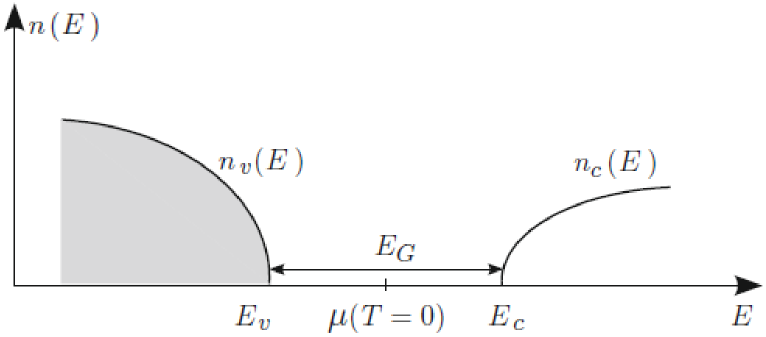
Table 1 Energy gap between the valence and conduction bands
(*i* = indirect gap; *d* = direct gap)

Crystal	Gap	E_g, eV 0 K	E_g, eV 300 K	Crystal	Gap	E_g, eV 0 K	E_g, eV 300 K
Diamond	*i*	5.4		SiC(hex)	*i*	3.0	—
Si	*i*	1.17	1.11	Te	*d*	0.33	—
Ge	*i*	0.744	0.66	HgTe[a]	*d*	−0.30	
αSn	*d*	0.00	0.00	PbS	*d*	0.286	0.34–0.37
InSb	*d*	0.23	0.17	PbSe	*i*	0.165	0.27
InAs	*d*	0.43	0.36	PbTe	*i*	0.190	0.29
InP	*d*	1.42	1.27	CdS	*d*	2.582	2.42
GaP	*i*	2.32	2.25	CdSe	*d*	1.840	1.74
GaAs	*d*	1.52	1.43	CdTe	*d*	1.607	1.44
GaSb	*d*	0.81	0.68	SnTe	*d*	0.3	0.18
AlSb	*i*	1.65	1.6	Cu_2O	*d*	2.172	—

[a]HgTe is a semimetal; the bands overlap.

Semicondutores Intrísecos

Semicondutores Intrísecos:
Livre de defeitos ou impurezas



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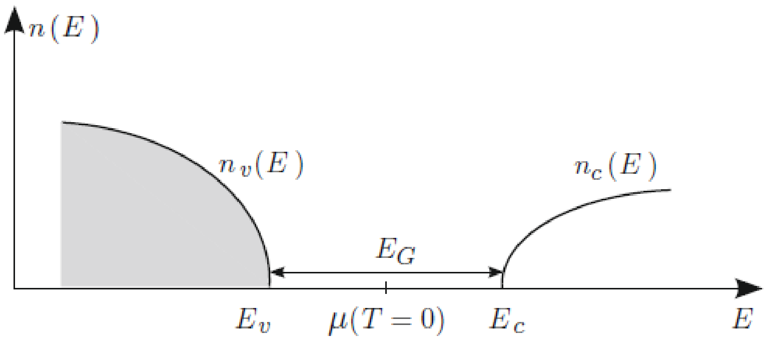

$$n_0(T) = N_c(T)e^{-(E_c-\mu)/k_BT}$$

$$N_c(T) \equiv \int_{E_c}^{\infty} n_c(E)e^{-(E-E_c)/k_BT}\,dE$$

$$p_0(T) = N_v(T)e^{-(\mu-E_v)/k_BT}$$

$$N_v(T) \equiv \int_{-\infty}^{E_v} n_v(E)e^{-(E_v-E)/k_BT}\,dE$$

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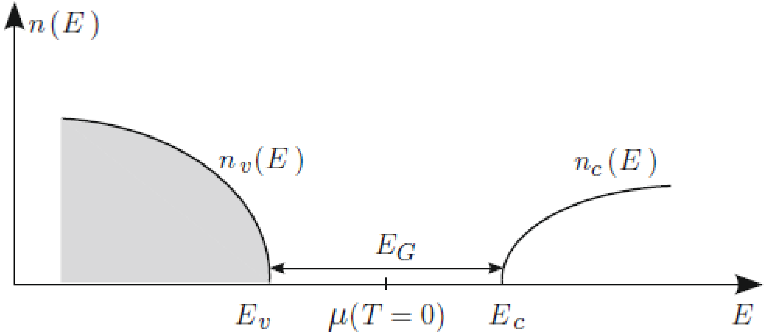

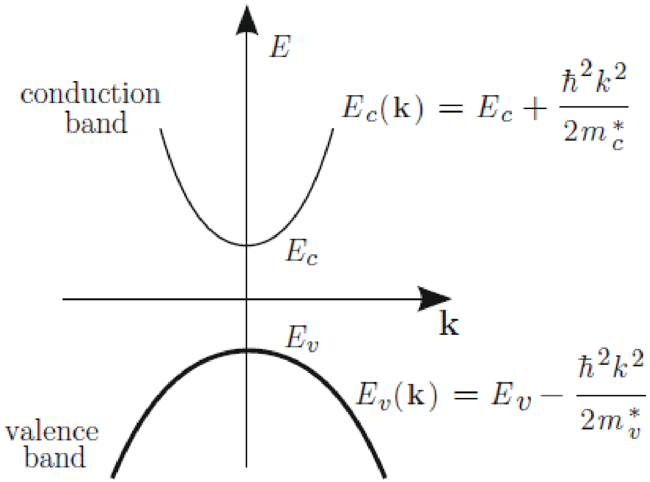

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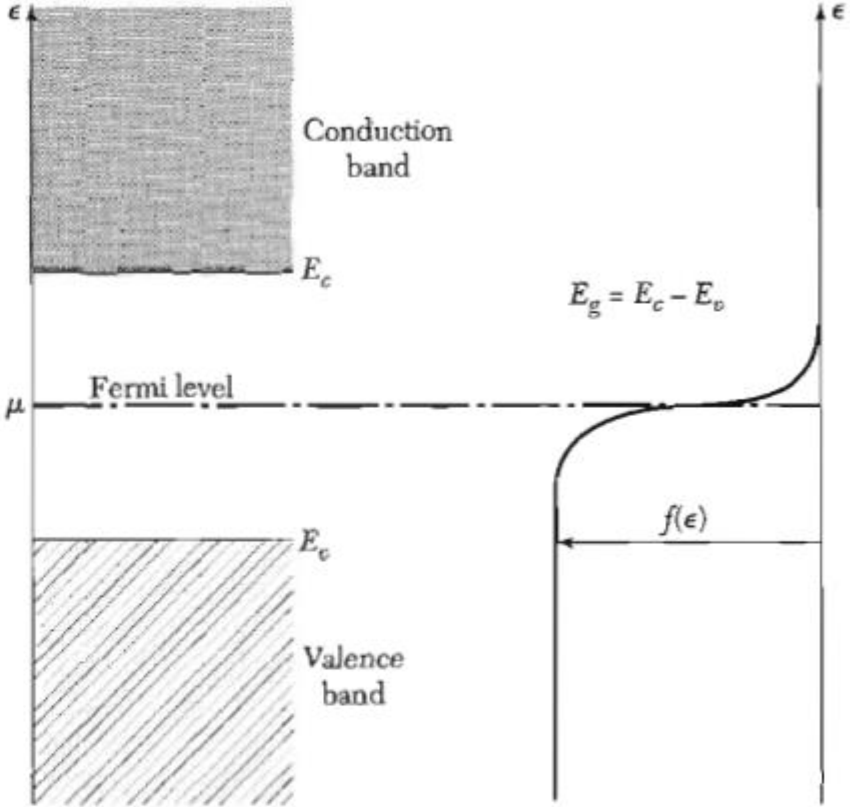
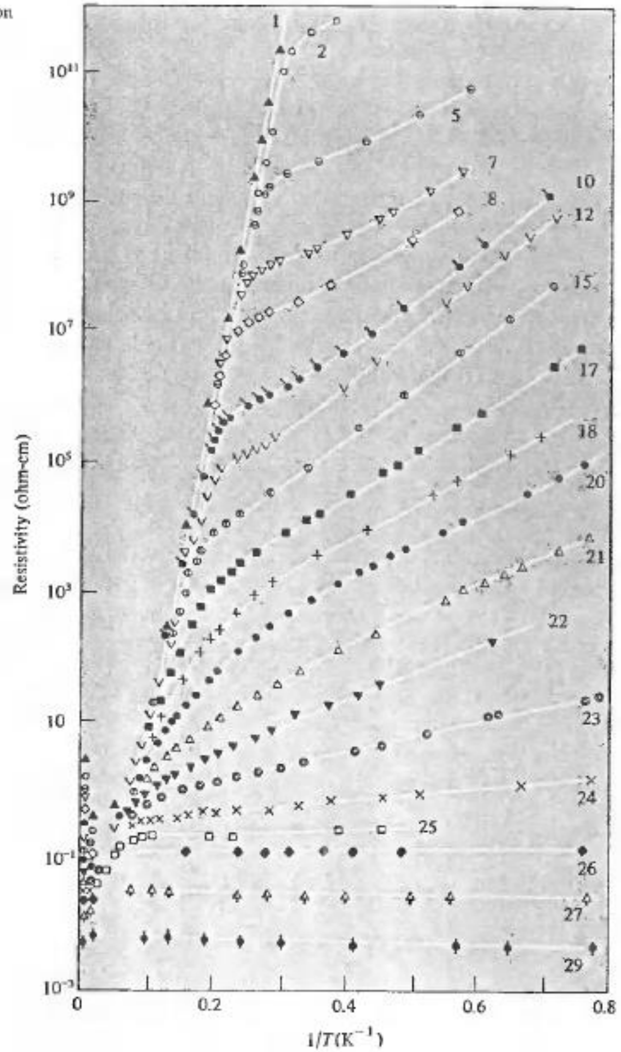


Si dopado com Sb

Specimen	Donor concentration (cm^{-3})
1	5.3×10^{14}
2	9.3×10^{14}
5	1.6×10^{15}
7	2.3×10^{15}
8	3.0×10^{15}
10	5.2×10^{15}
12	8.5×10^{15}
15	1.3×10^{16}
17	2.4×10^{16}
18	3.5×10^{16}
20	4.5×10^{16}
21	5.5×10^{16}
22	6.4×10^{16}
23	7.4×10^{16}
24	8.4×10^{16}
25	1.2×10^{17}
26	1.3×10^{17}
27	2.7×10^{17}
29	9.5×10^{17}



Periodic Table of the Elements

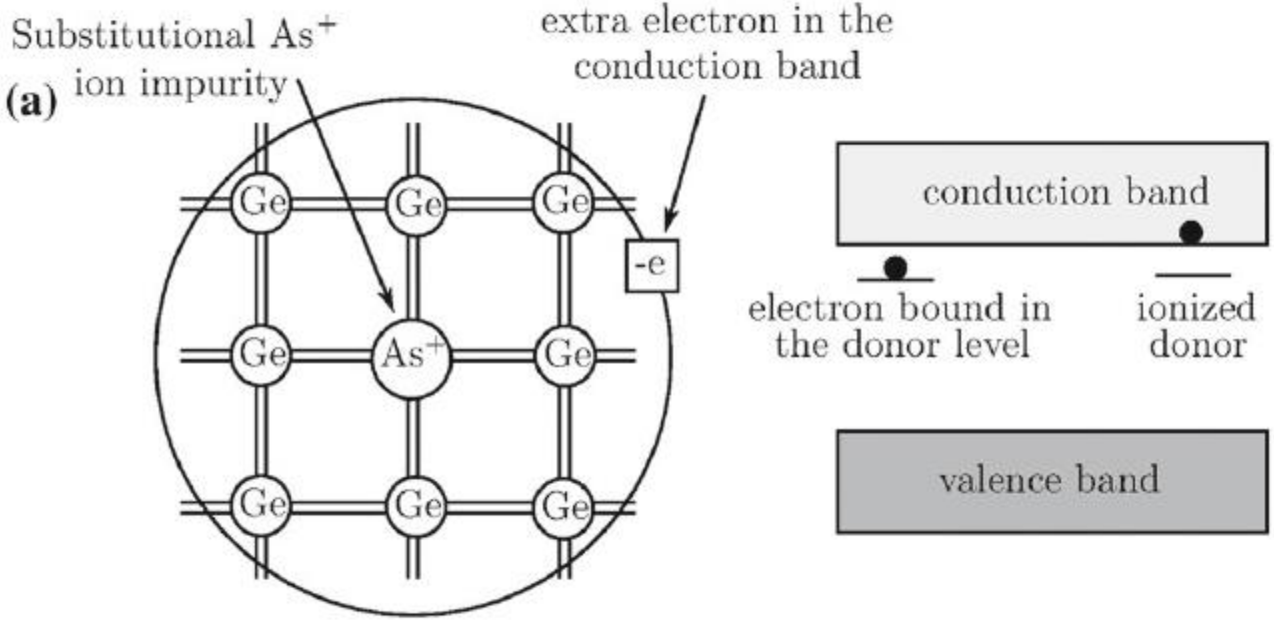
Atomic Number → 13 | Al ← Symbol | Name → Aluminium | 26.982 ← Atomic Weight | Electrons per shell → 2-8-3

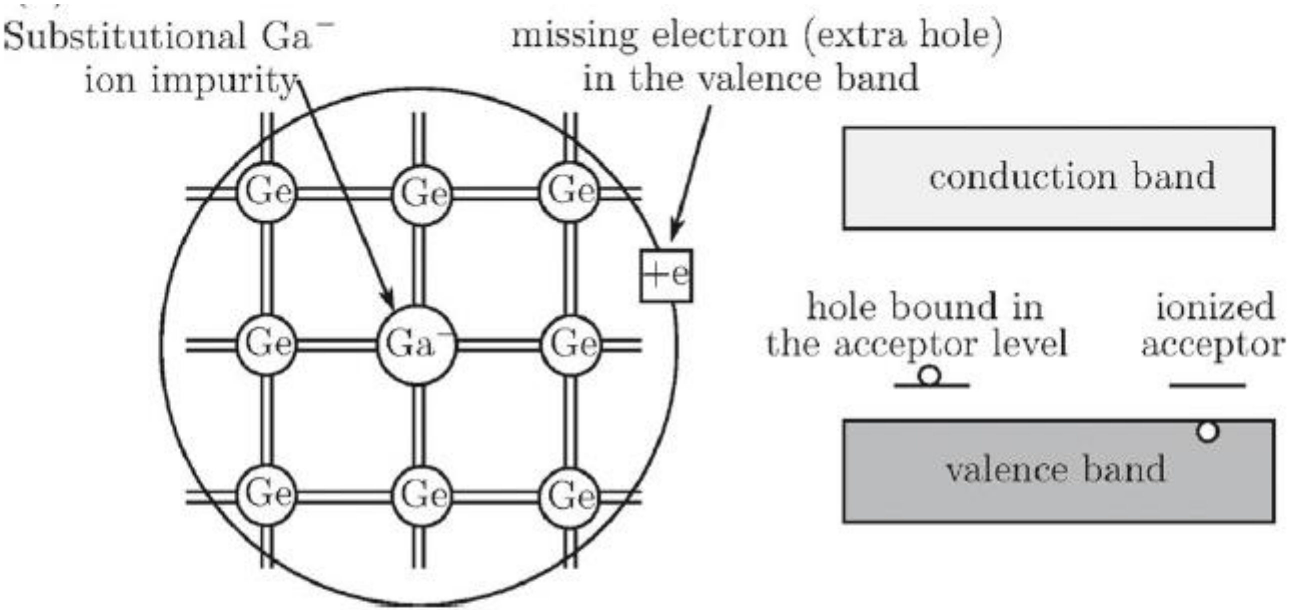
State of matter (color of name): GAS, LIQUID, SOLID, UNKNOWN

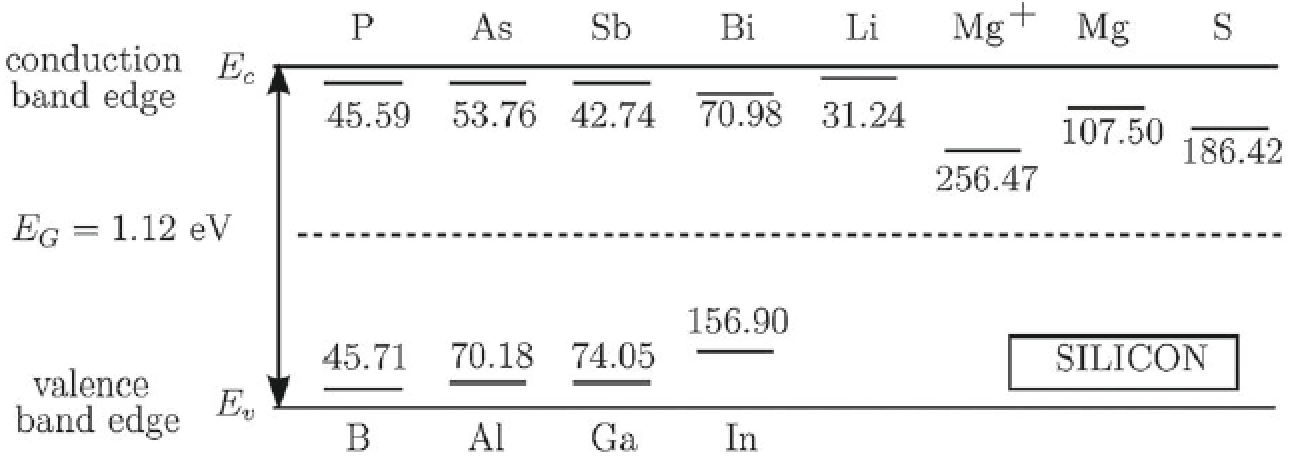
Subcategory in the metal-metalloid-nonmetal trend (color of background):
- Alkali metals
- Alkaline earth metals
- Transition metals
- Lanthanides
- Actinides
- Post-transition metals
- Metalloids
- Reactive nonmetals
- Noble gases
- Unknown chemical properties

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 **H** Hydrogen 1.008 1																	2 **He** Helium 4.0026 2
3 **Li** Lithium 6.94 2-1	4 **Be** Beryllium 9.0122 2-2											5 **B** Boron 10.81 2-3	6 **C** Carbon 12.011 2-4	7 **N** Nitrogen 14.007 2-5	8 **O** Oxygen 15.999 2-6	9 **F** Fluorine 18.998 2-7	10 **Ne** Neon 20.180 2-8
11 **Na** Sodium 22.98976928 2-8-1	12 **Mg** Magnesium 24.305 2-8-2											13 **Al** Aluminium 26.982 2-8-3	14 **Si** Silicon 28.085 2-8-4	15 **P** Phosphorus 30.974 2-8-5	16 **S** Sulfur 32.06 2-8-6	17 **Cl** Chlorine 35.45 2-8-7	18 **Ar** Argon 39.948 2-8-8
19 **K** Potassium 39.0983 2-8-8-1	20 **Ca** Calcium 40.078 2-8-8-2	21 **Sc** Scandium 44.955908 2-8-9-2	22 **Ti** Titanium 47.867 2-8-10-2	23 **V** Vanadium 50.9415 2-8-11-2	24 **Cr** Chromium 51.9961 2-8-13-1	25 **Mn** Manganese 54.938044 2-8-13-2	26 **Fe** Iron 55.845 2-8-14-2	27 **Co** Cobalt 58.933 2-8-15-2	28 **Ni** Nickel 58.693 2-8-16-2	29 **Cu** Copper 63.546 2-8-18-1	30 **Zn** Zinc 65.38 2-8-18-2	31 **Ga** Gallium 69.723 2-8-18-3	32 **Ge** Germanium 72.630 2-8-18-4	33 **As** Arsenic 74.922 2-8-18-5	34 **Se** Selenium 78.971 2-8-18-6	35 **Br** Bromine 79.904 2-8-18-7	36 **Kr** Krypton 83.798 2-8-18-8
37 **Rb** Rubidium 85.4678 2-8-18-8-1	38 **Sr** Strontium 87.62 2-8-18-8-2	39 **Y** Yttrium 88.90584 2-8-18-9-2	40 **Zr** Zirconium 91.224 2-8-18-10-2	41 **Nb** Niobium 92.90637 2-8-18-12-1	42 **Mo** Molybdenum 95.95 2-8-18-13-1	43 **Tc** Technetium (98) 2-8-18-13-2	44 **Ru** Ruthenium 101.07 2-8-18-15-1	45 **Rh** Rhodium 102.91 2-8-18-16-1	46 **Pd** Palladium 106.42 2-8-18-18	47 **Ag** Silver 107.87 2-8-18-18-1	48 **Cd** Cadmium 112.41 2-8-18-18-2	49 **In** Indium 114.82 2-8-18-18-3	50 **Sn** Tin 118.71 2-8-18-18-4	51 **Sb** Antimony 121.76 2-8-18-18-5	52 **Te** Tellurium 127.60 2-8-18-18-6	53 **I** Iodine 126.90 2-8-18-18-7	54 **Xe** Xenon 131.29 2-8-18-18-8
55 **Cs** Caesium 132.90545196 2-8-18-18-8-1	56 **Ba** Barium 137.327 2-8-18-18-8-2	57-71 Lanthanides	72 **Hf** Hafnium 178.49 2-8-18-32-10-2	73 **Ta** Tantalum 180.94788 2-8-18-32-11-2	74 **W** Tungsten 183.84 2-8-18-32-12-2	75 **Re** Rhenium 186.21 2-8-18-32-13-2	76 **Os** Osmium 190.23 2-8-18-32-14-2	77 **Ir** Iridium 192.22 2-8-18-32-15-2	78 **Pt** Platinum 195.08 2-8-18-32-17-1	79 **Au** Gold 196.97 2-8-18-32-18-1	80 **Hg** Mercury 200.59 2-8-18-32-18-2	81 **Tl** Thallium 204.38 2-8-18-32-18-3	82 **Pb** Lead 207.2 2-8-18-32-18-4	83 **Bi** Bismuth 208.98 2-8-18-32-18-5	84 **Po** Polonium (209) 2-8-18-32-18-6	85 **At** Astatine (210) 2-8-18-32-18-7	86 **Rn** Radon (222) 2-8-18-32-18-8
87 **Fr** Francium (223) 2-8-18-32-18-8-1	88 **Ra** Radium (226) 2-8-18-32-18-8-2	89-103 Actinides	104 **Rf** Rutherfordium (267) 2-8-18-32-32-10-2	105 **Db** Dubnium (268) 2-8-18-32-32-11-2	106 **Sg** Seaborgium (269) 2-8-18-32-32-12-2	107 **Bh** Bohrium (270) 2-8-18-32-32-13-2	108 **Hs** Hassium (277) 2-8-18-32-32-14-2	109 **Mt** Meitnerium (278) 2-8-18-32-32-15-2	110 **Ds** Darmstadtium (281) 2-8-18-32-32-17-1	111 **Rg** Roentgenium (282) 2-8-18-32-32-17-2	112 **Cn** Copernicium (285) 2-8-18-32-32-18-2	113 **Nh** Nihonium (286) 2-8-18-32-32-18-3	114 **Fl** Flerovium (289) 2-8-18-32-32-18-4	115 **Mc** Moscovium (290) 2-8-18-32-32-18-5	116 **Lv** Livermorium (293) 2-8-18-32-32-18-6	117 **Ts** Tennessine (294) 2-8-18-32-32-18-7	118 **Og** Oganesson (294) 2-8-18-32-32-18-8

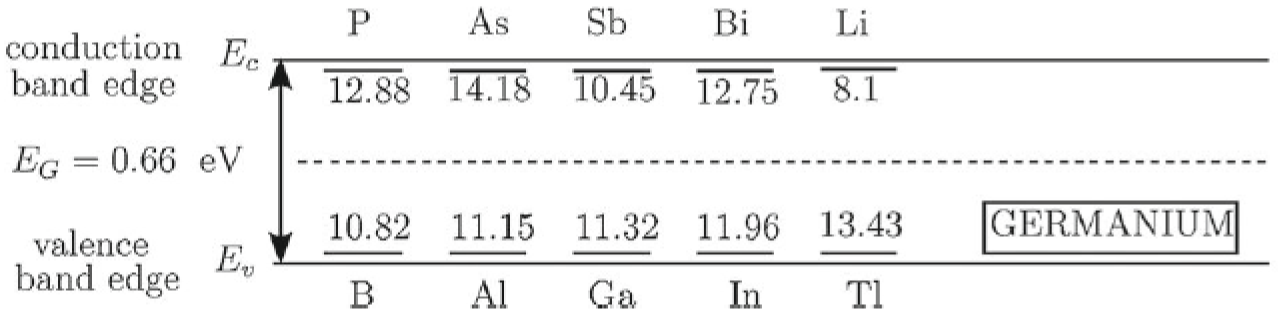
57 **La** Lanthanum 138.91 2-8-18-18-9-2	58 **Ce** Cerium 140.12 2-8-18-19-9-2	59 **Pr** Praseodymium 140.91 2-8-18-21-8-2	60 **Nd** Neodymium 144.24 2-8-18-22-8-2	61 **Pm** Promethium (145) 2-8-18-23-8-2	62 **Sm** Samarium 150.36 2-8-18-24-8-2	63 **Eu** Europium 151.96 2-8-18-25-8-2	64 **Gd** Gadolinium 157.25 2-8-18-25-9-2	65 **Tb** Terbium 158.93 2-8-18-27-8-2	66 **Dy** Dysprosium 162.50 2-8-18-28-8-2	67 **Ho** Holmiun 164.93 2-8-18-29-8-2	68 **Er** Erbium 167.26 2-8-18-30-8-2	69 **Tm** Thulium 168.93 2-8-18-31-8-2	70 **Yb** Ytterbium 173.05 2-8-18-32-8-2	71 **Lu** Lutetium 174.97 2-8-18-32-9-2
89 **Ac** Actinium (227) 2-8-18-32-18-9-2	90 **Th** Thorium 232.04 2-8-18-32-18-10-2	91 **Pa** Protactinium 231.04 2-8-18-32-20-9-2	92 **U** Uranium 238.03 2-8-18-32-21-9-2	93 **Np** Neptunium (237) 2-8-18-32-22-9-2	94 **Pu** Plutonium (244) 2-8-18-32-24-8-2	95 **Am** Americium (243) 2-8-18-32-25-8-2	96 **Cm** Curium (247) 2-8-18-32-25-9-2	97 **Bk** Berkelium (247) 2-8-18-32-27-8-2	98 **Cf** Californium (251) 2-8-18-32-28-8-2	99 **Es** Einsteinium (252) 2-8-18-32-29-8-2	100 **Fm** Fermium (257) 2-8-18-32-30-8-2	101 **Md** Mendelevium (258) 2-8-18-32-31-8-2	102 **No** Nobelium (259) 2-8-18-32-32-8-2	103 **Lr** Lawrencium (266) 2-8-18-32-32-8-3


(a)
Substitutional As$^+$
ion impurity
extra electron in the
conduction band
Ge
As$^+$
-e
conduction band
electron bound in
the donor level
ionized
donor
valence band

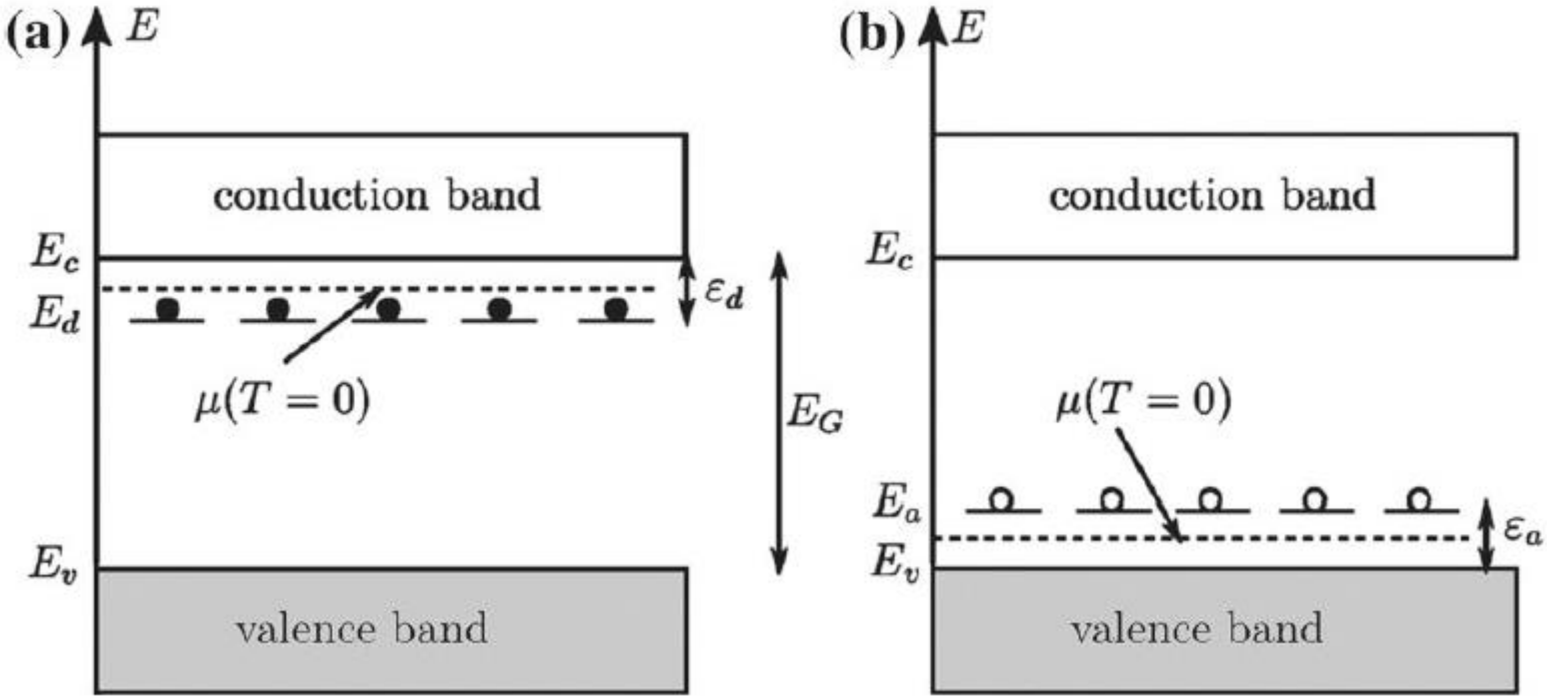

Substitutional Ga⁻
ion impurity
missing electron (extra hole)
in the valence band
Ge
Ga⁻
+e
conduction band
hole bound in
the acceptor level
ionized
acceptor
valence band



P
As
Sb
Bi
Li
Mg+
Mg
S
conduction band edge
E_c
45.59
53.76
42.74
70.98
31.24
256.47
107.50
186.42
$E_G = 1.12$ eV
156.90
45.71
70.18
74.05
SILICON
valence band edge
E_v
B
Al
Ga
In



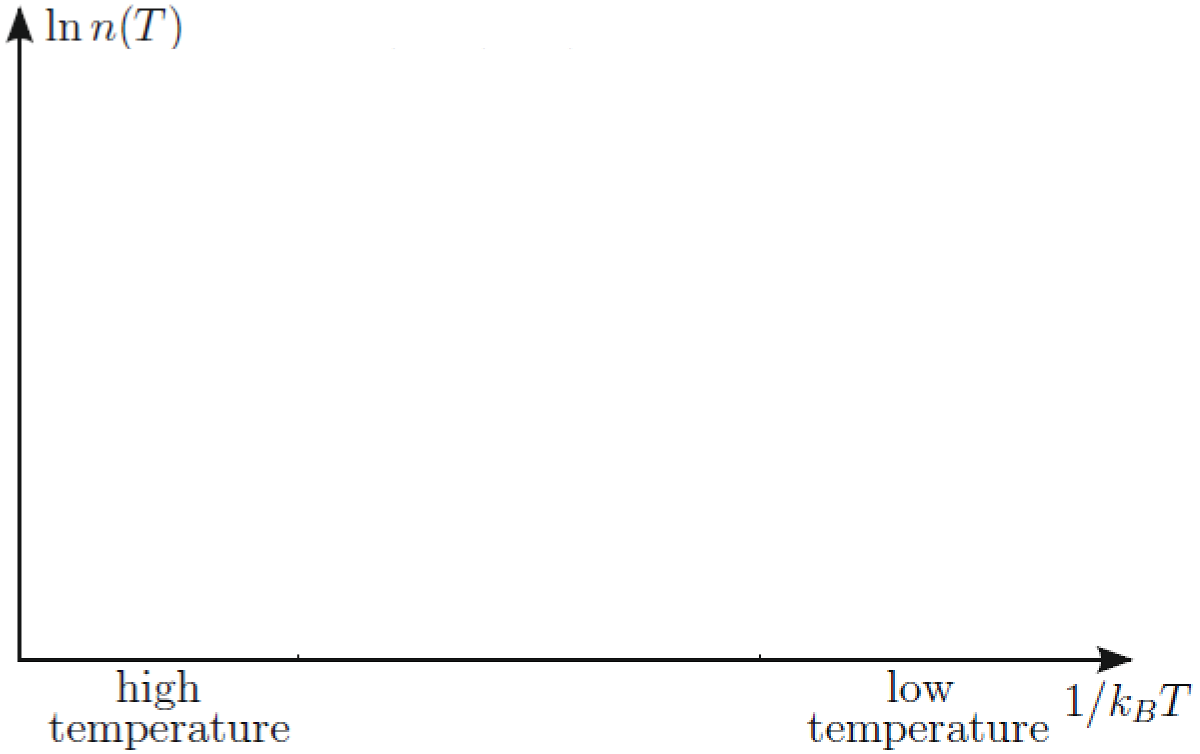
P
As
Sb
Bi
Li
conduction band edge
E_c
12.88
14.18
10.45
12.75
8.1
$E_G = 0.66$ eV
10.82
11.15
11.32
11.96
13.43
GERMANIUM
valence band edge
E_v
B
Al
Ga
In
Tl



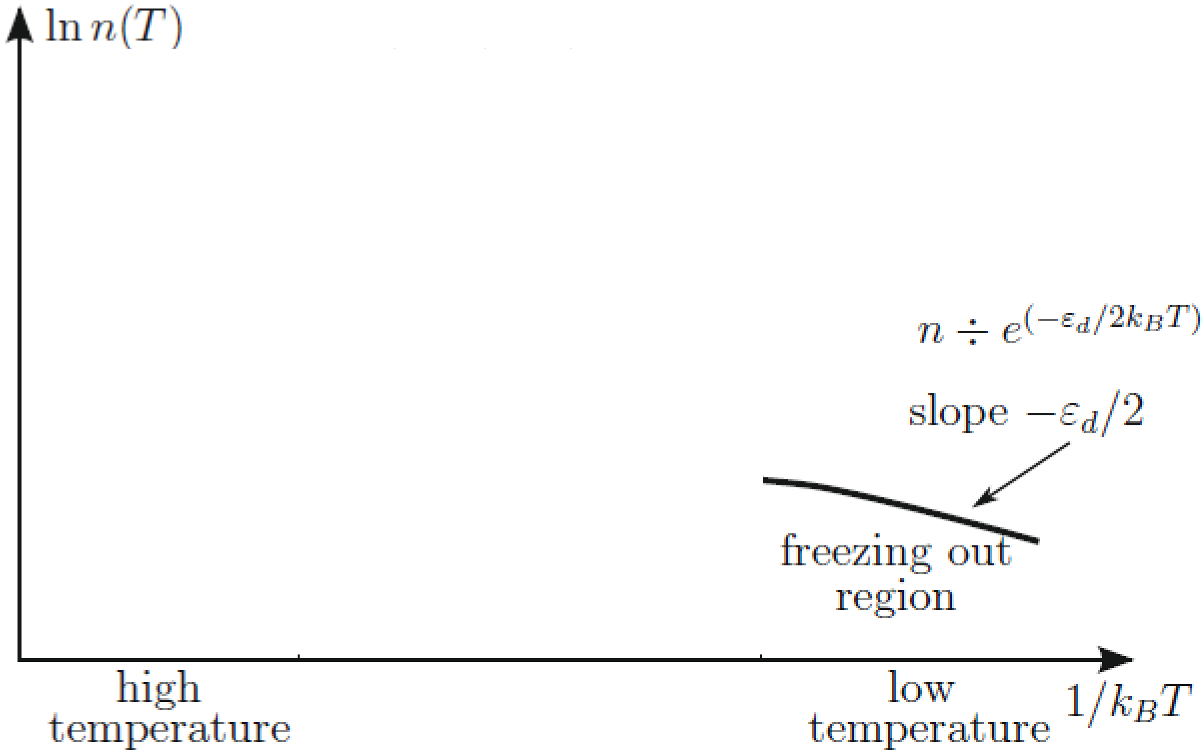
(a)
E
conduction band
E_c
E_d
ε_d
$\mu(T = 0)$
E_G
E_v
valence band
(b)
E
conduction band
E_c
$\mu(T = 0)$
E_a
ε_a
E_v
valence band

$$N_c(T)e^{-(E_c-\mu)/k_BT} = N_d \frac{(1/2)e^{(E_d-\mu)/k_BT}}{(1/2)e^{(E_d-\mu)/k_BT}+1} + N_v(T)e^{-(\mu-E_v)/k_BT}$$

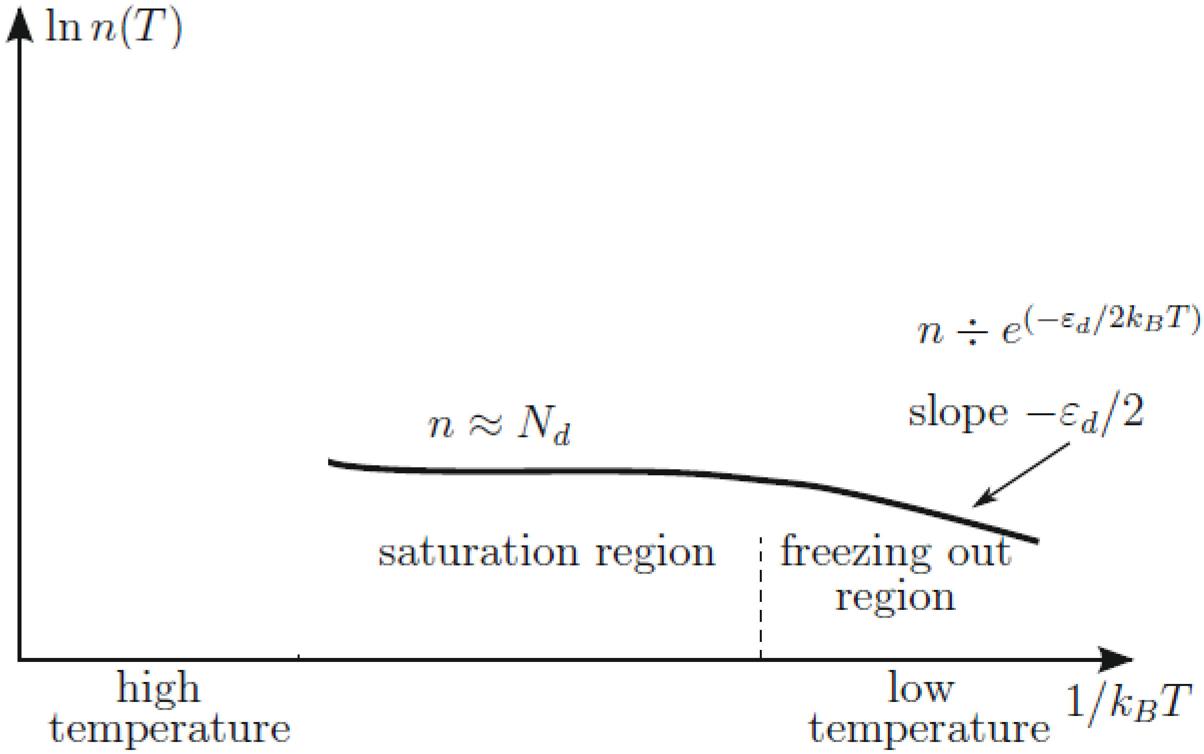
$$N_c(T)e^{-(E_c-\mu)/k_BT} = N_d \frac{(1/2)e^{(E_d-\mu)/k_BT}}{(1/2)e^{(E_d-\mu)/k_BT}+1} + N_v(T)e^{-(\mu-E_v)/k_BT}$$



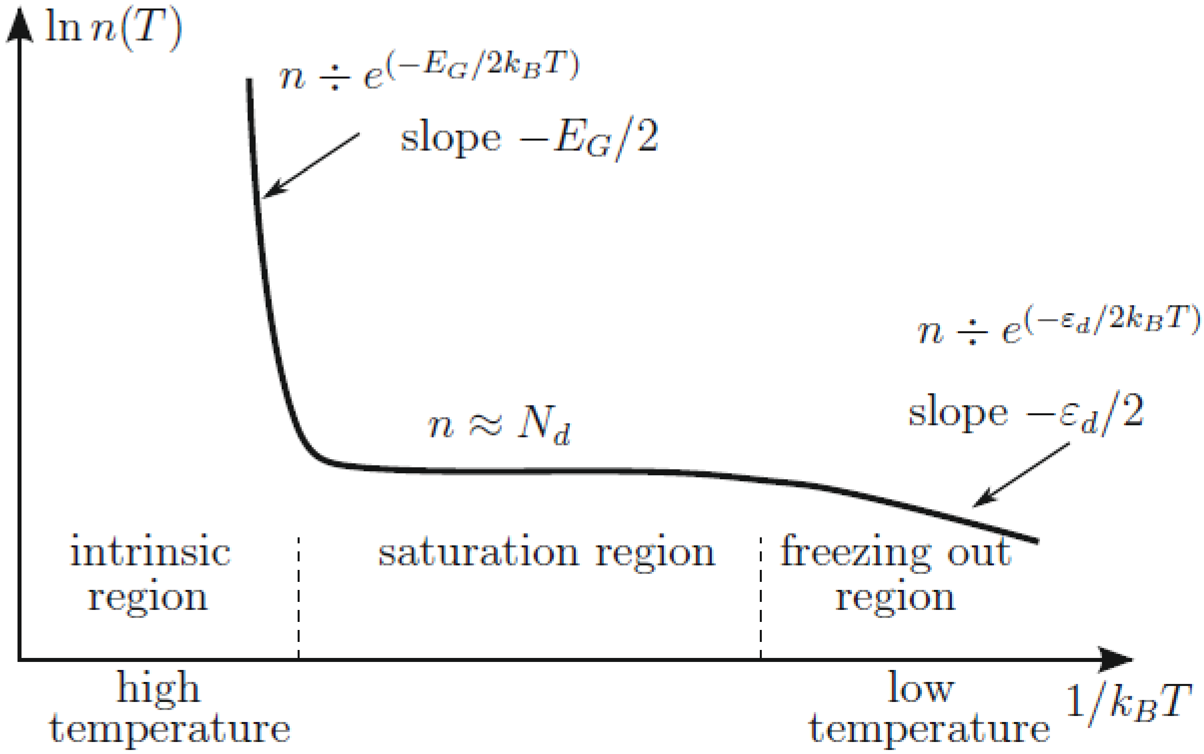
$$N_c(T)e^{-(E_c-\mu)/k_BT} = N_d\frac{(1/2)e^{(E_d-\mu)/k_BT}}{(1/2)e^{(E_d-\mu)/k_BT}+1} + N_v(T)e^{-(\mu-E_v)/k_BT}$$

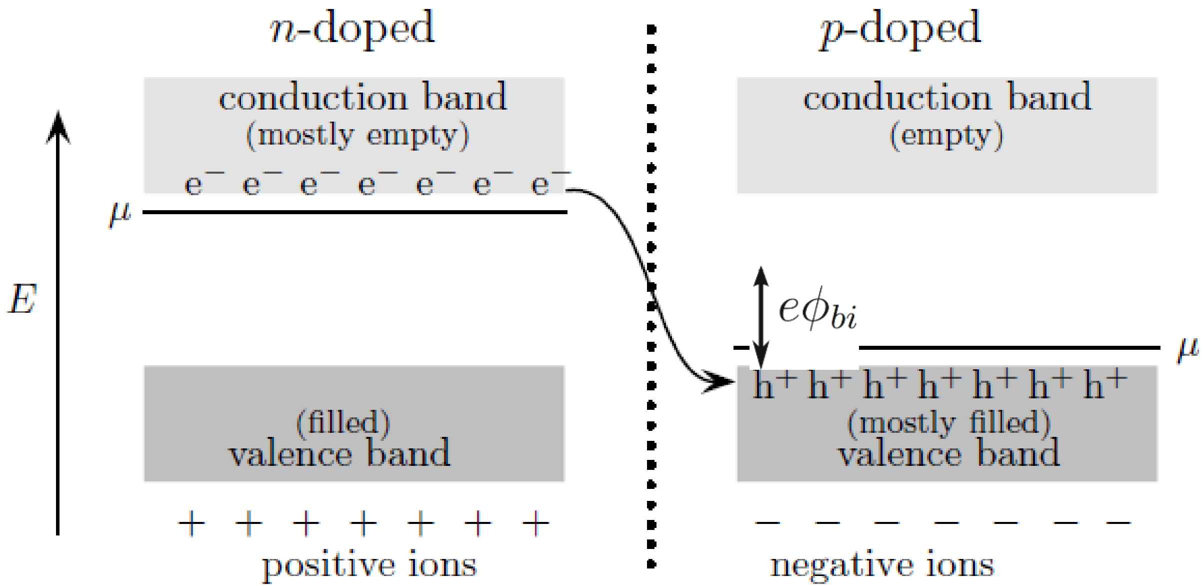


$$N_c(T)e^{-(E_c-\mu)/k_BT} = N_d\frac{(1/2)e^{(E_d-\mu)/k_BT}}{(1/2)e^{(E_d-\mu)/k_BT}+1} + N_v(T)e^{-(\mu-E_v)/k_BT}$$

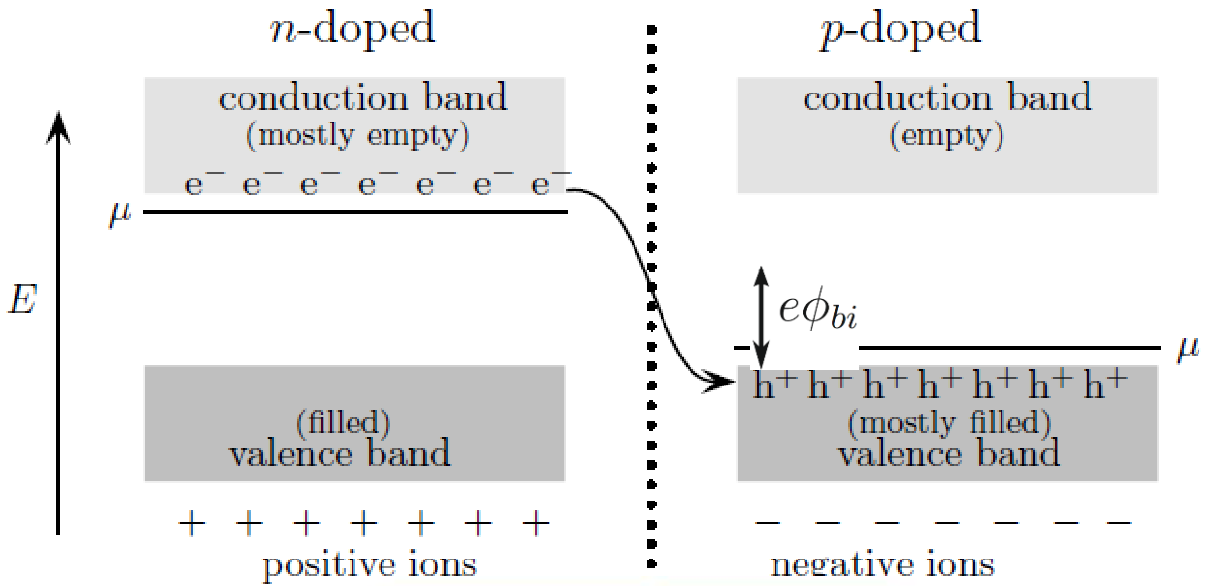


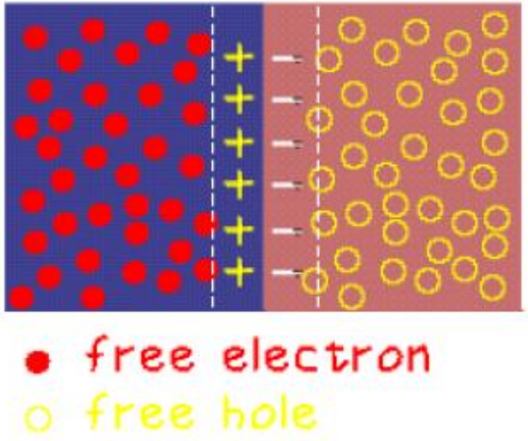
$$N_c(T)e^{-(E_c-\mu)/k_BT} = N_d \frac{(1/2)e^{(E_d-\mu)/k_BT}}{(1/2)e^{(E_d-\mu)/k_BT}+1} + N_v(T)e^{-(\mu-E_v)/k_BT}$$

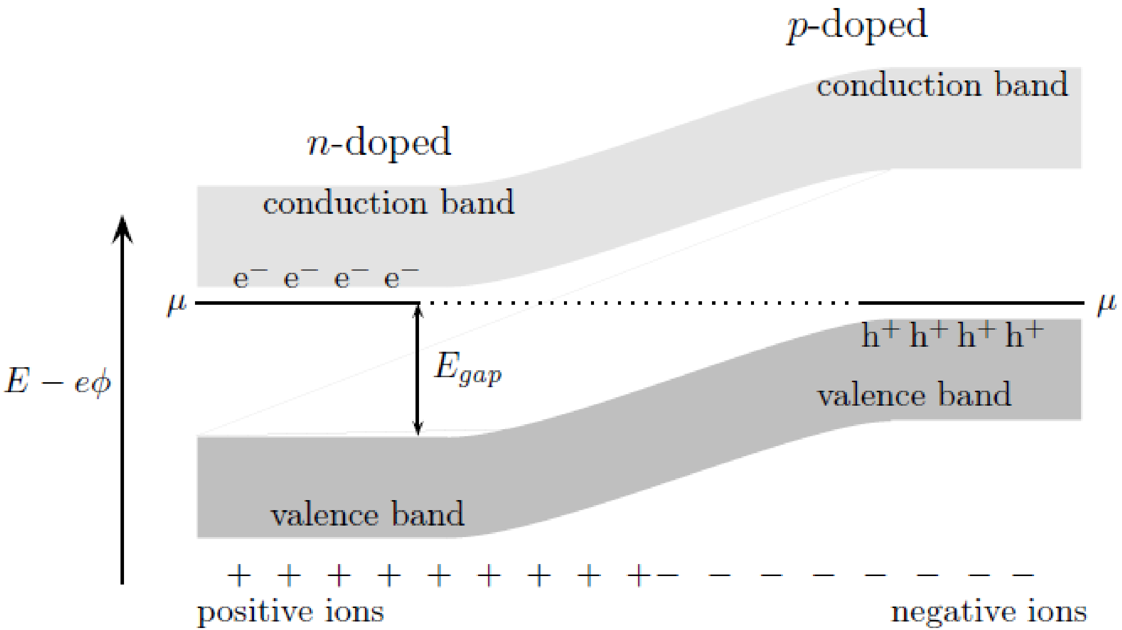




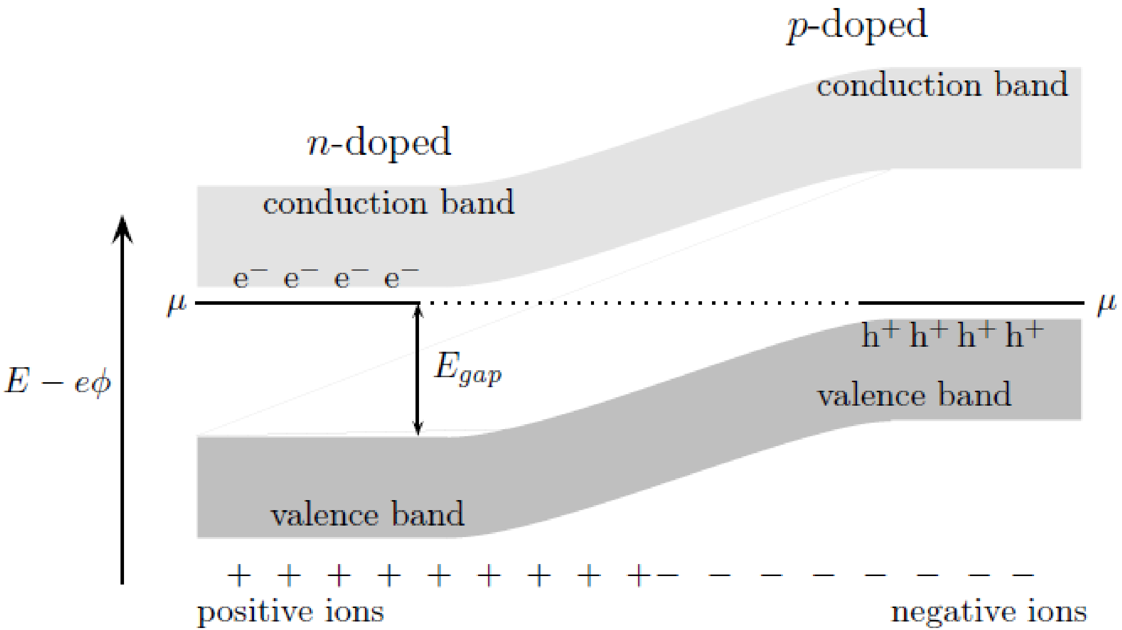
n-doped
p-doped
conduction band
(mostly empty)
conduction band
(empty)
e⁻ e⁻ e⁻ e⁻ e⁻ e⁻ e⁻
μ
E
eφ_bi
μ
h⁺ h⁺ h⁺ h⁺ h⁺ h⁺ h⁺
(filled)
valence band
(mostly filled)
valence band
+ + + + + + +
positive ions
− − − − − − −
negative ions


n-doped
p-doped
conduction band
(mostly empty)
conduction band
(empty)
e⁻ e⁻ e⁻ e⁻ e⁻ e⁻ e⁻
μ
E
eφ_bi
μ
h⁺ h⁺ h⁺ h⁺ h⁺ h⁺ h⁺
(mostly filled)
valence band
(filled)
valence band
+ + + + + + +
positive ions
− − − − − − −
negative ions

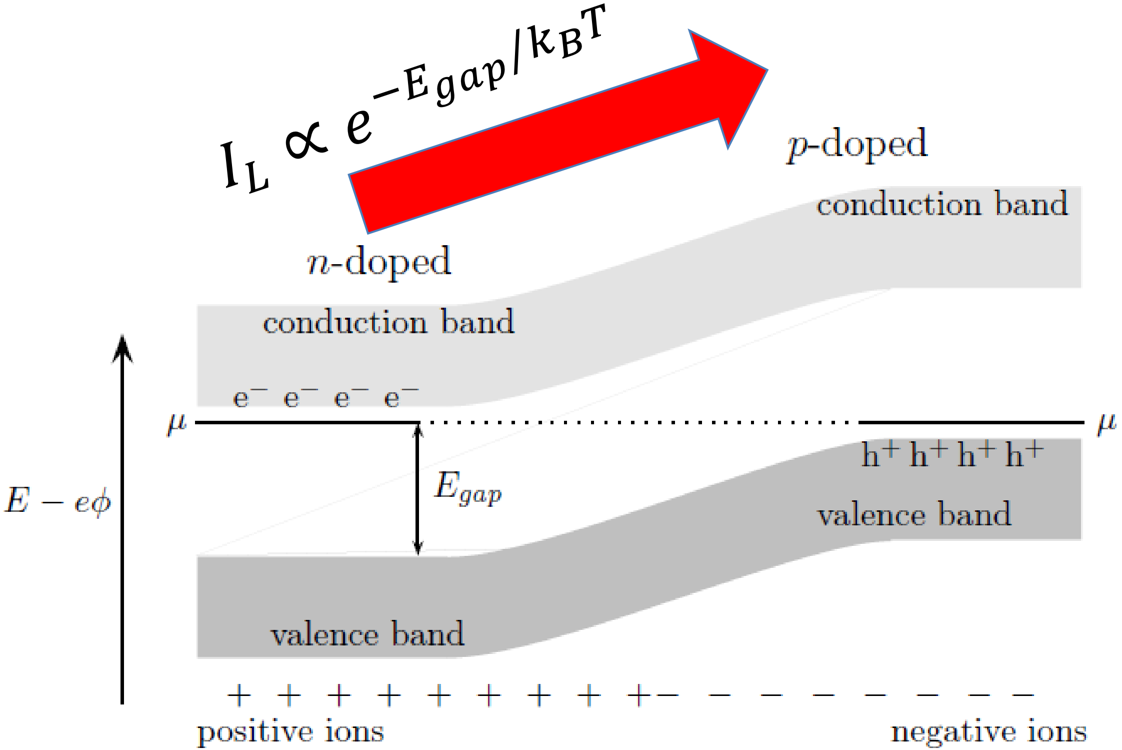

free electron
free hole



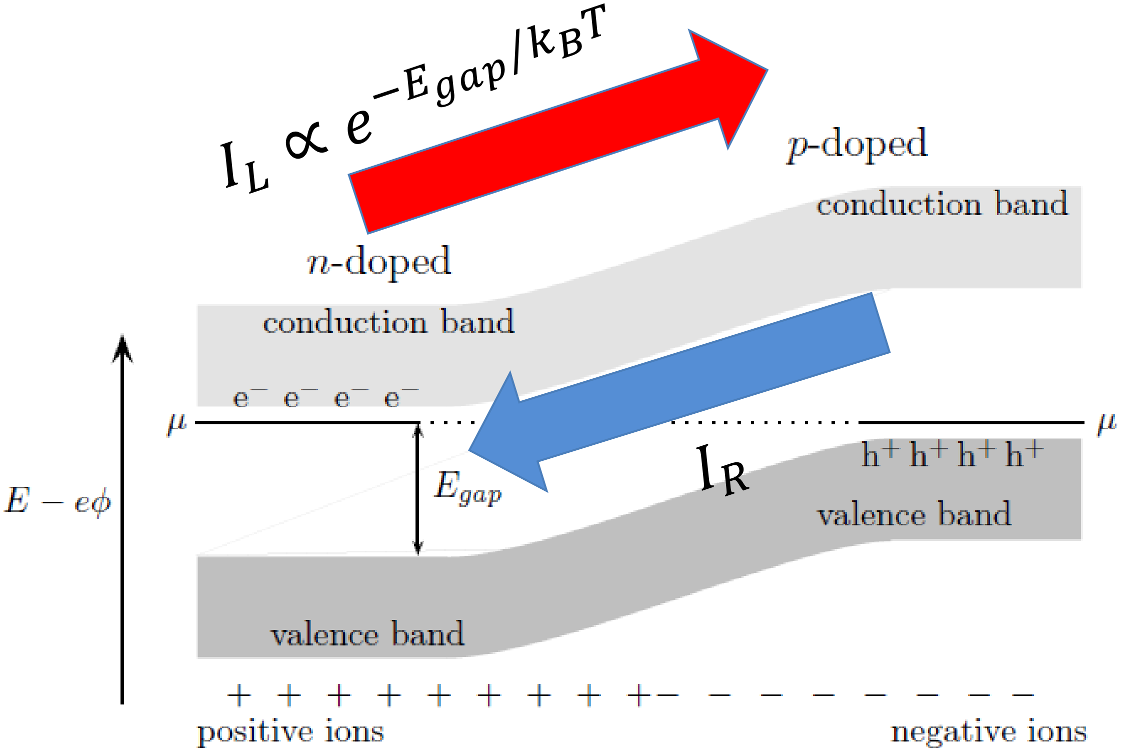
p-doped
conduction band
n-doped
conduction band
e^- e^- e^- e^-
μ
μ
h^+ h^+ h^+ h^+
$E - e\phi$
E_{gap}
valence band
valence band
+ + + + + + + + + − − − − − − − −
positive ions
negative ions


p-doped
conduction band
n-doped
conduction band
e⁻ e⁻ e⁻ e⁻
μ
μ
h⁺ h⁺ h⁺ h⁺
E_{gap}
$E - e\phi$
valence band
valence band
+ + + + + + + + + − − − − − − − −
positive ions
negative ions

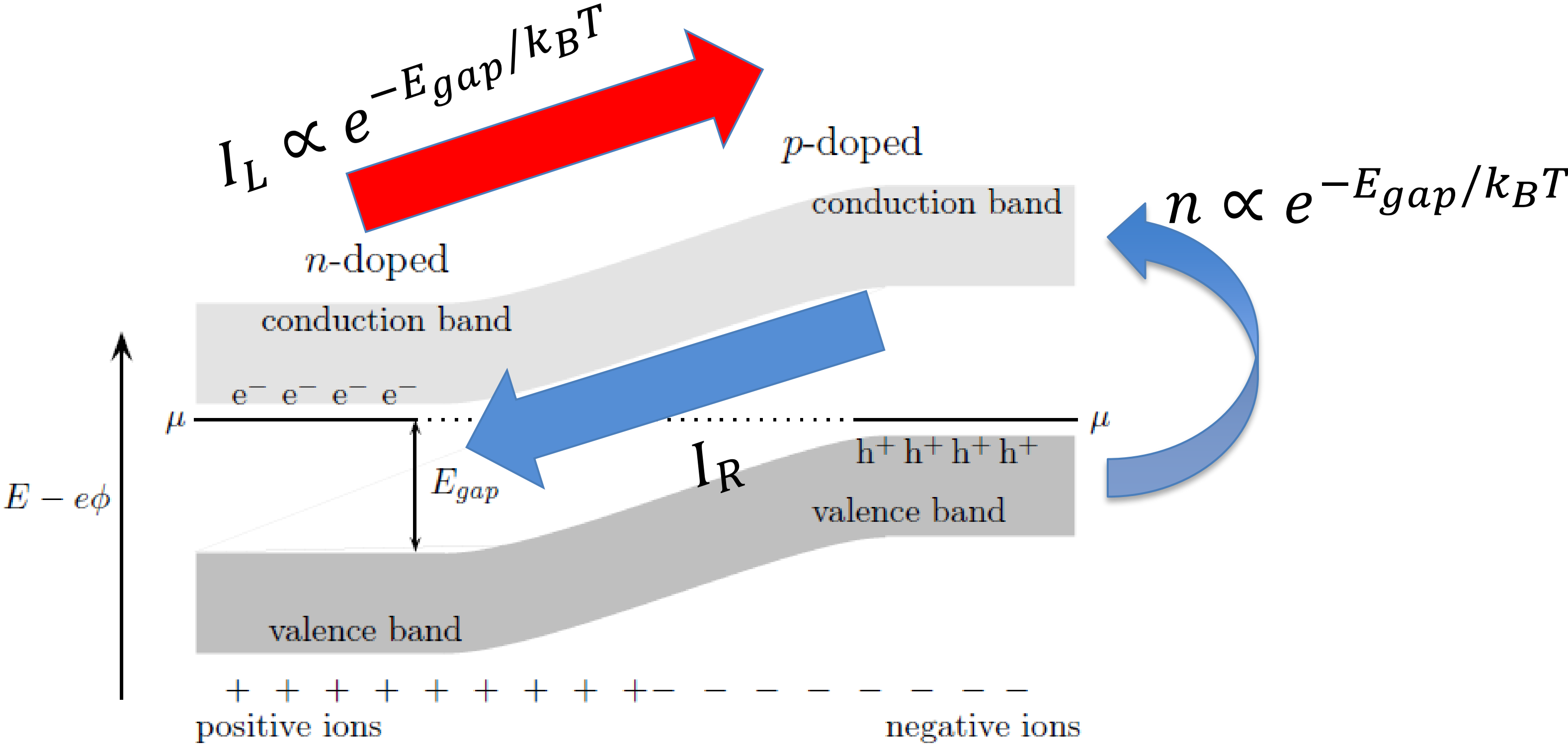
$$I_{total} = I_L - I_R$$


$I_L \propto e^{-E_{gap}/k_B T}$
p-doped
conduction band
n-doped
conduction band
$e^- \; e^- \; e^- \; e^-$
μ
μ
$h^+ \, h^+ \, h^+ \, h^+$
E_{gap}
$E - e\phi$
valence band
valence band
+ + + + + + + + +− − − − − − − −
positive ions
negative ions

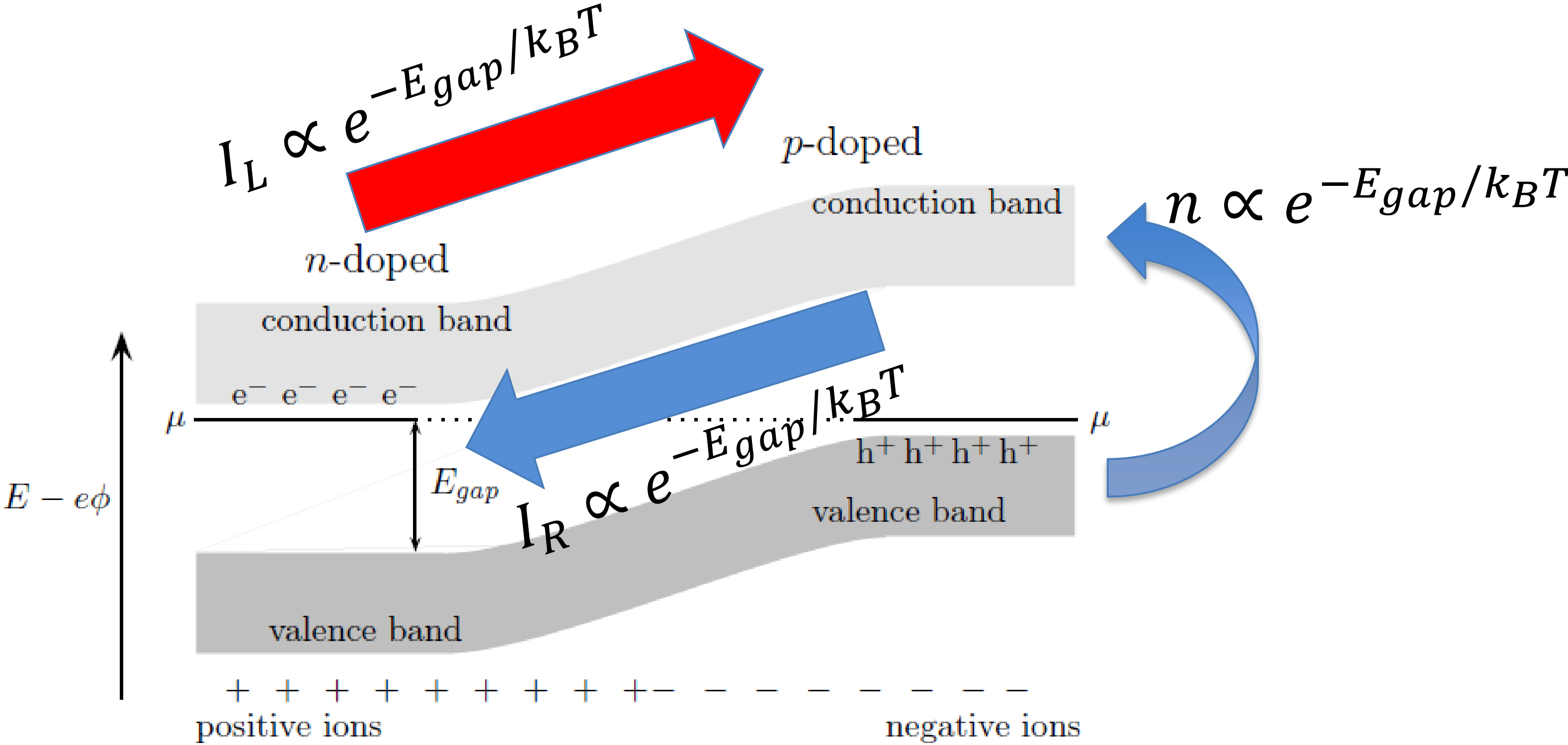
$$I_{total} = I_L - I_R$$


$I_L \propto e^{-E_{gap}/k_BT}$
p-doped
conduction band
n-doped
conduction band
e⁻ e⁻ e⁻ e⁻
μ
μ
h⁺ h⁺ h⁺ h⁺
I_R
$E - e\phi$
E_{gap}
valence band
valence band
+ + + + + + + + +− − − − − − − −
positive ions
negative ions

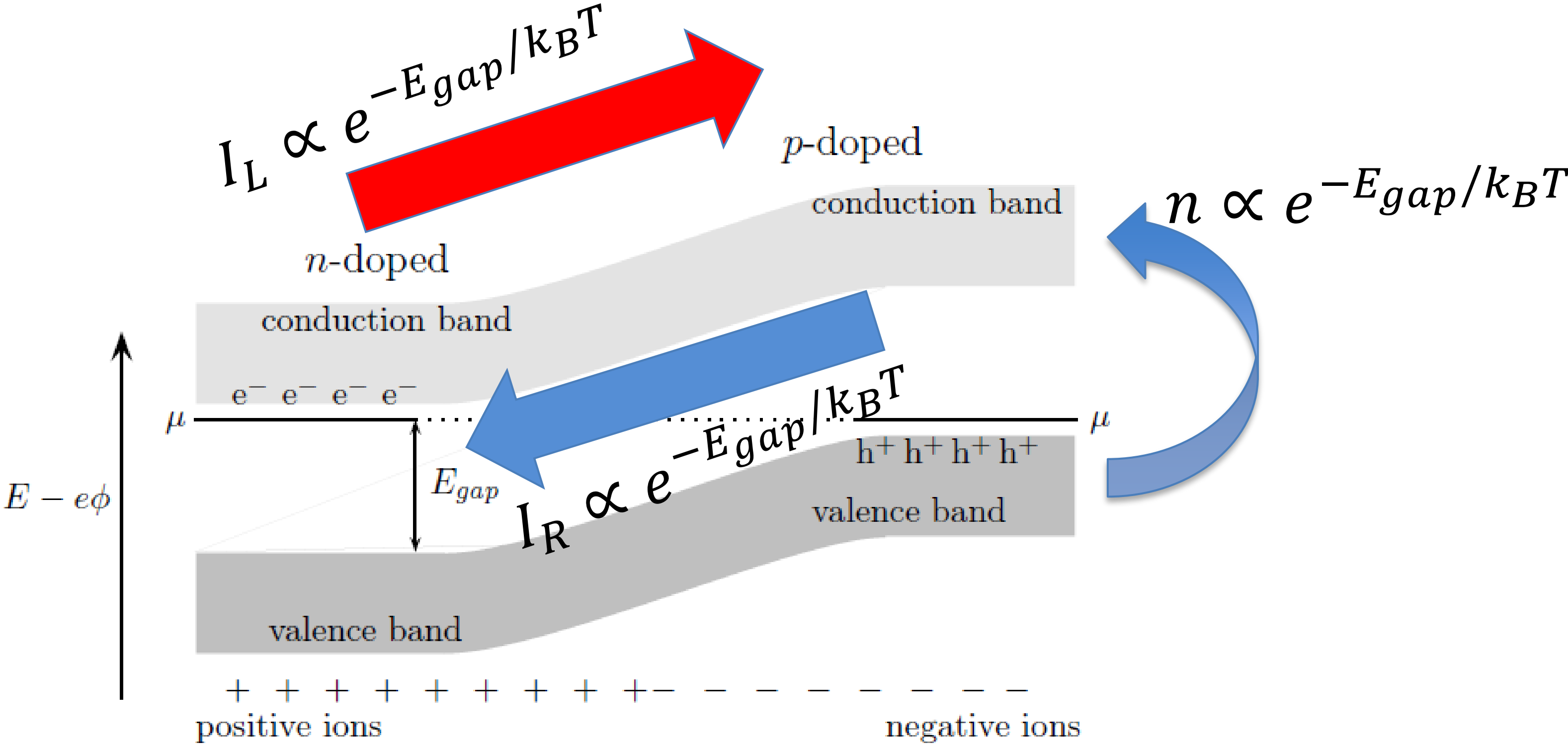
$$I_{total} = I_L - I_R$$


$I_L \propto e^{-E_{gap}/k_BT}$
p-doped
conduction band
$n \propto e^{-E_{gap}/k_BT}$
n-doped
conduction band
e⁻ e⁻ e⁻ e⁻
μ
μ
E_{gap}
I_R
h⁺ h⁺ h⁺ h⁺
valence band
$E - e\phi$
valence band
positive ions
negative ions

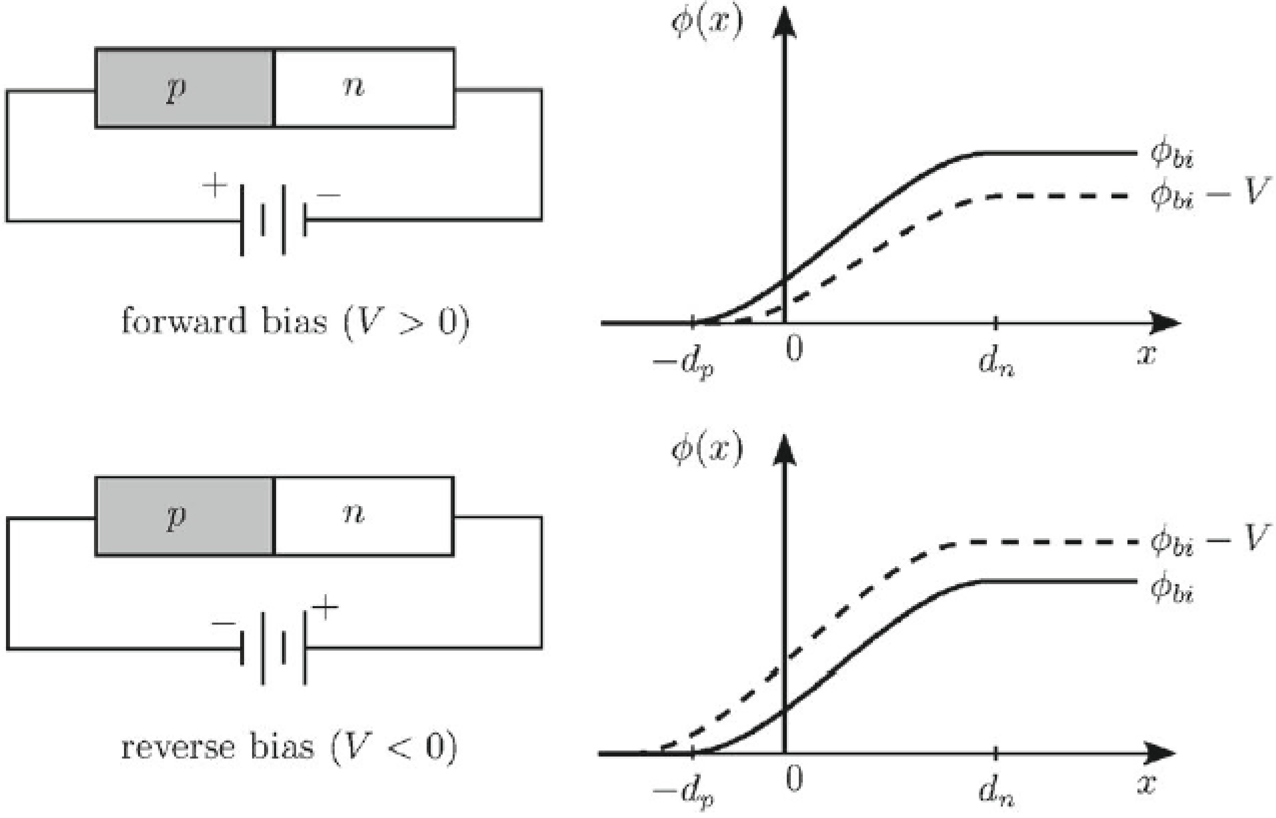
$$I_{total} = I_L - I_R$$

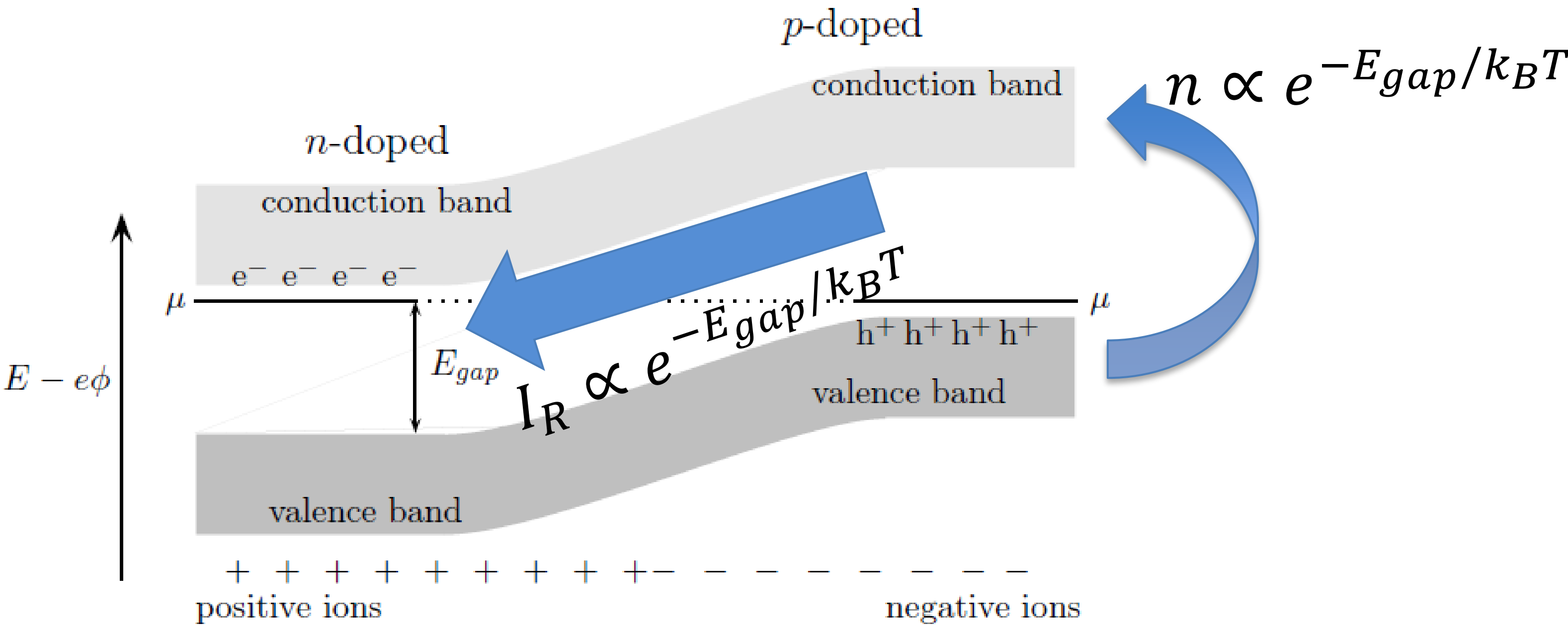

$I_L \propto e^{-E_{gap}/k_BT}$
p-doped
conduction band
$n \propto e^{-E_{gap}/k_BT}$
n-doped
conduction band
e^- e^- e^- e^-
μ
μ
$I_R \propto e^{-E_{gap}/k_BT}$
h^+ h^+ h^+ h^+
E_{gap}
$E - e\phi$
valence band
valence band
+ + + + + + + + + − − − − − − − −
positive ions
negative ions

$$I_{total} = I_L - I_R$$

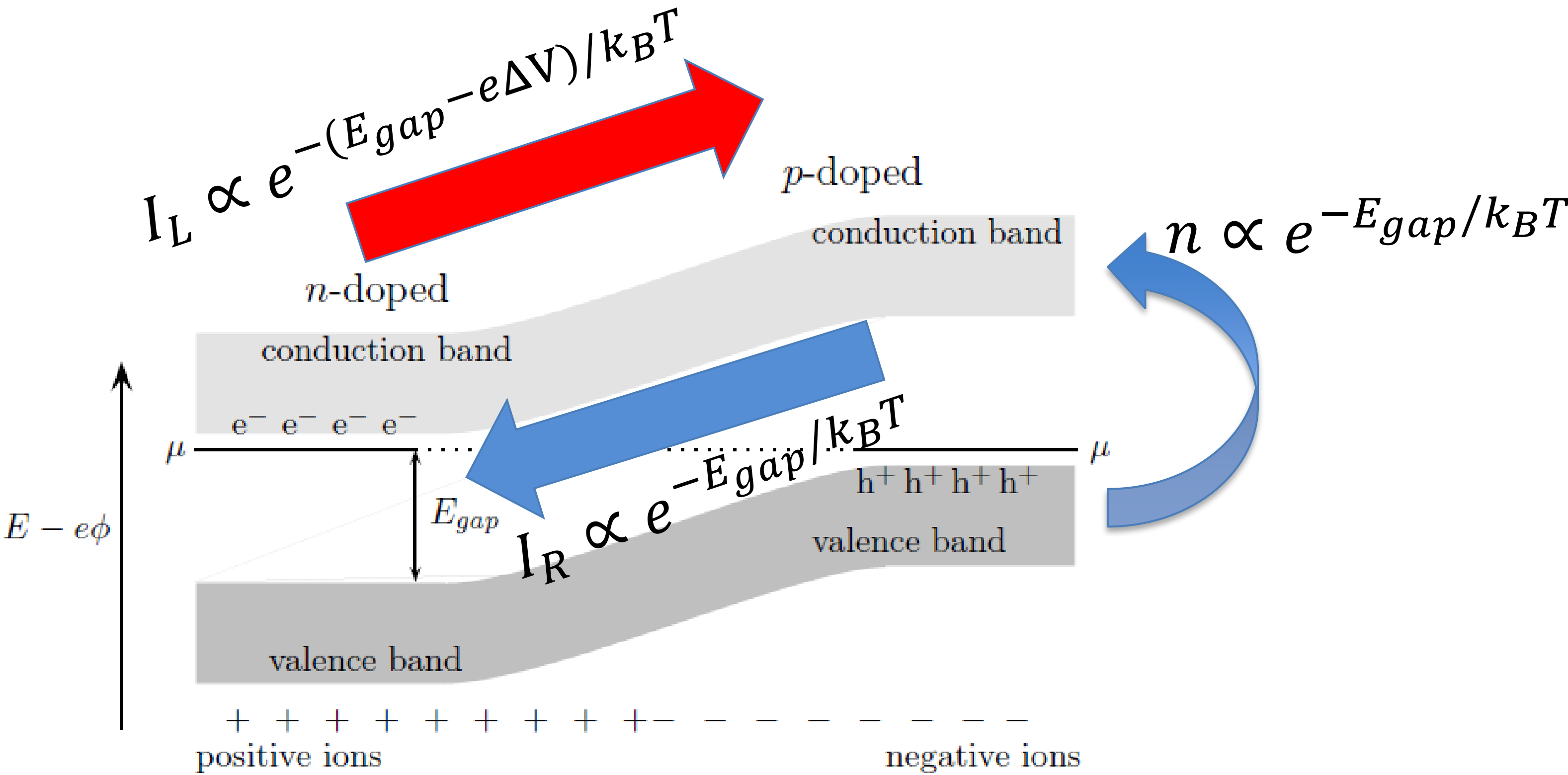


$$I_{total} = I_L - I_R = 0$$


p
n
+
−
forward bias (V > 0)
φ(x)
φ_bi
φ_bi − V
−d_p
0
d_n
x
p
n
−
+
reverse bias (V < 0)
φ(x)
φ_bi − V
φ_bi
−d_p
0
d_n
x

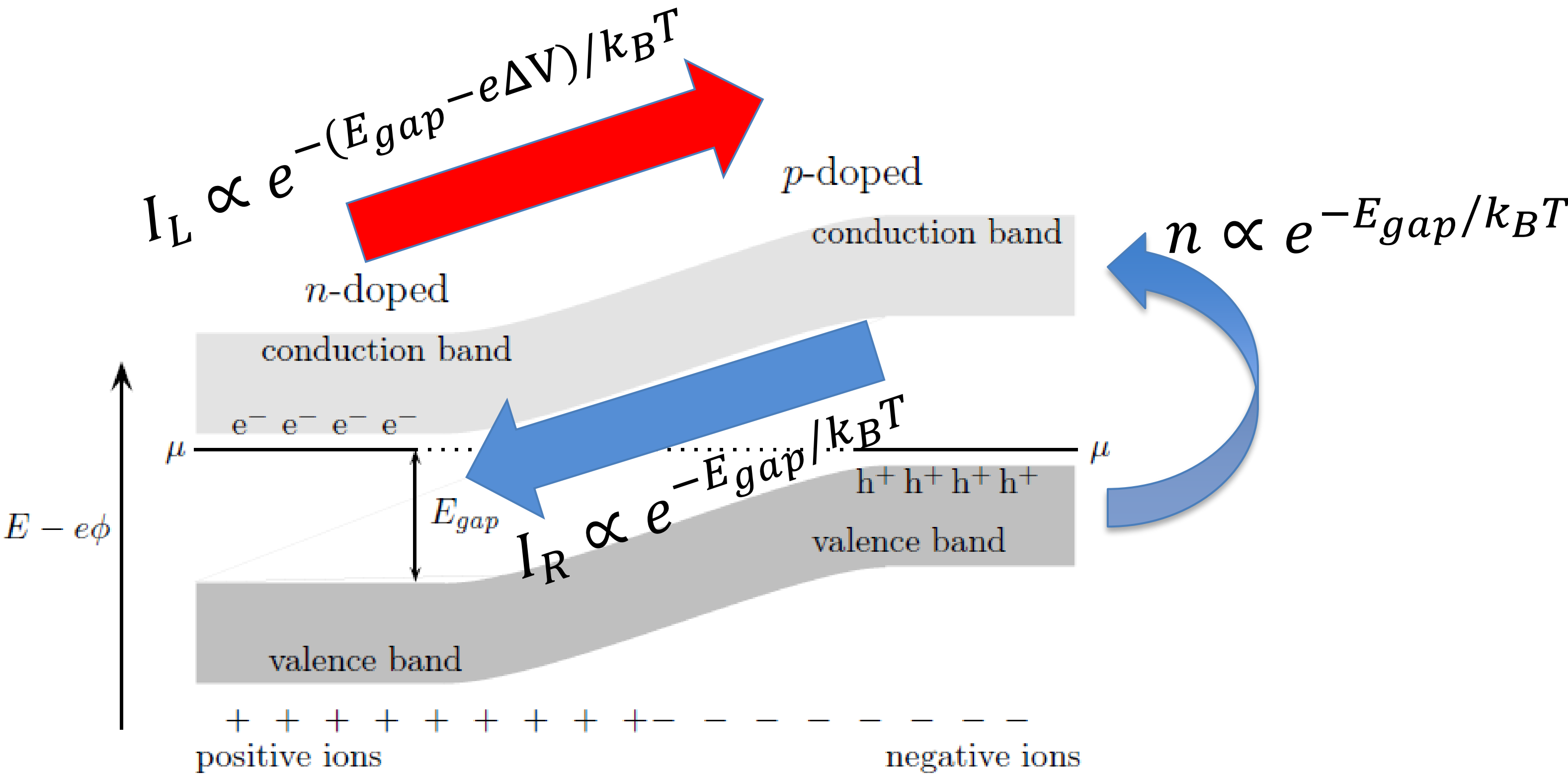

p-doped
conduction band
$n \propto e^{-E_{gap}/k_BT}$
n-doped
conduction band
e⁻ e⁻ e⁻ e⁻
μ
μ
E_{gap}
$I_R \propto e^{-E_{gap}/k_BT}$
h⁺ h⁺ h⁺ h⁺
valence band
$E - e\phi$
valence band
+ + + + + + + + + − − − − − − − −
positive ions
negative ions

$$I_{total} = I_L - I_R$$

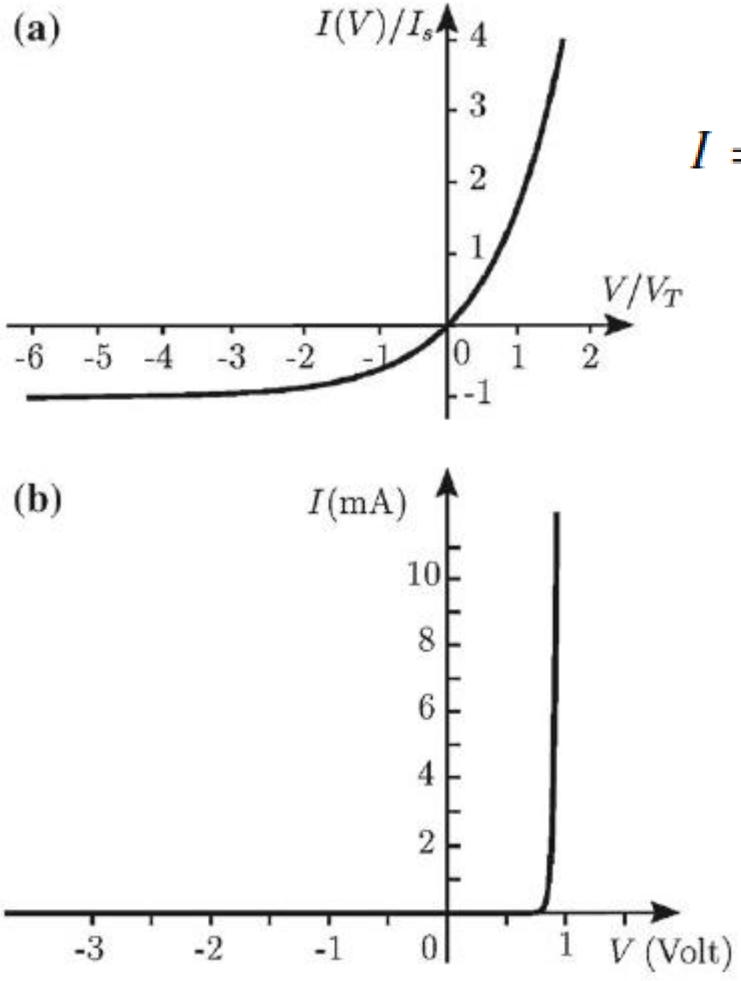


$I_L \propto e^{-(E_{gap}-e\Delta V)/k_B T}$
p-doped
conduction band
$n \propto e^{-E_{gap}/k_B T}$
n-doped
conduction band
e⁻ e⁻ e⁻ e⁻
μ
μ
E_{gap}
h⁺ h⁺ h⁺ h⁺
$E - e\phi$
$I_R \propto e^{-E_{gap}/k_B T}$
valence band
valence band
+ + + + + + + + + − − − − − − − −
positive ions
negative ions

$$I_{total} = I_L - I_R$$



$$I_{total} = I_L - I_R \propto e^{-\frac{E_{gap}}{k_BT}}\left(e^{e\Delta V/k_BT} - 1\right)$$

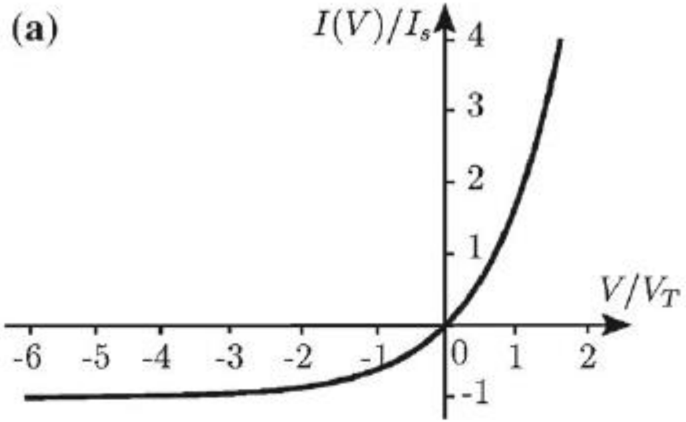


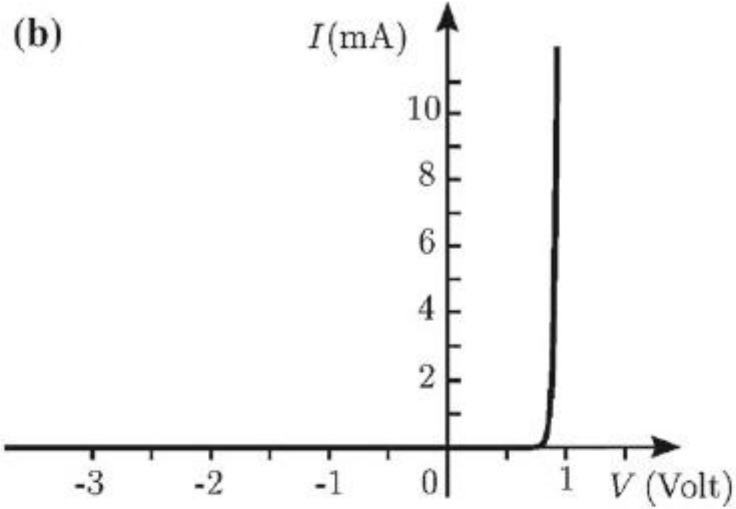
$$I = I_s \left(e^{V/V_T} - 1\right)$$

$$eV_T \equiv k_B T$$

$$I_s \approx 10^{-15} A$$

$$V_T = 25 \text{ mV}$$





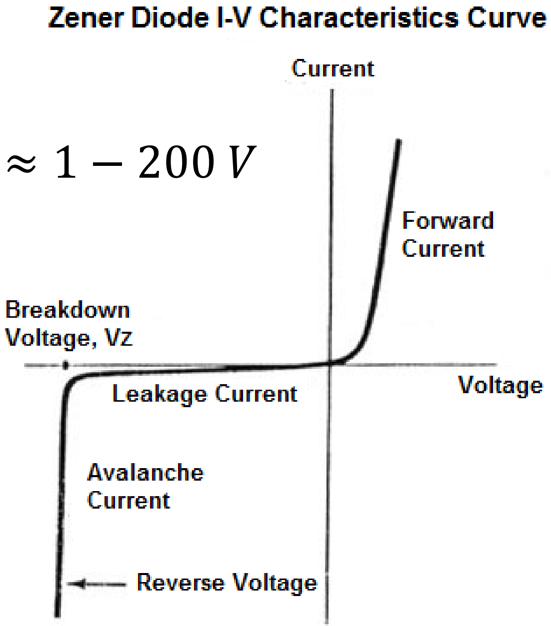
$$I = I_s\left(e^{V/V_T} - 1\right)$$

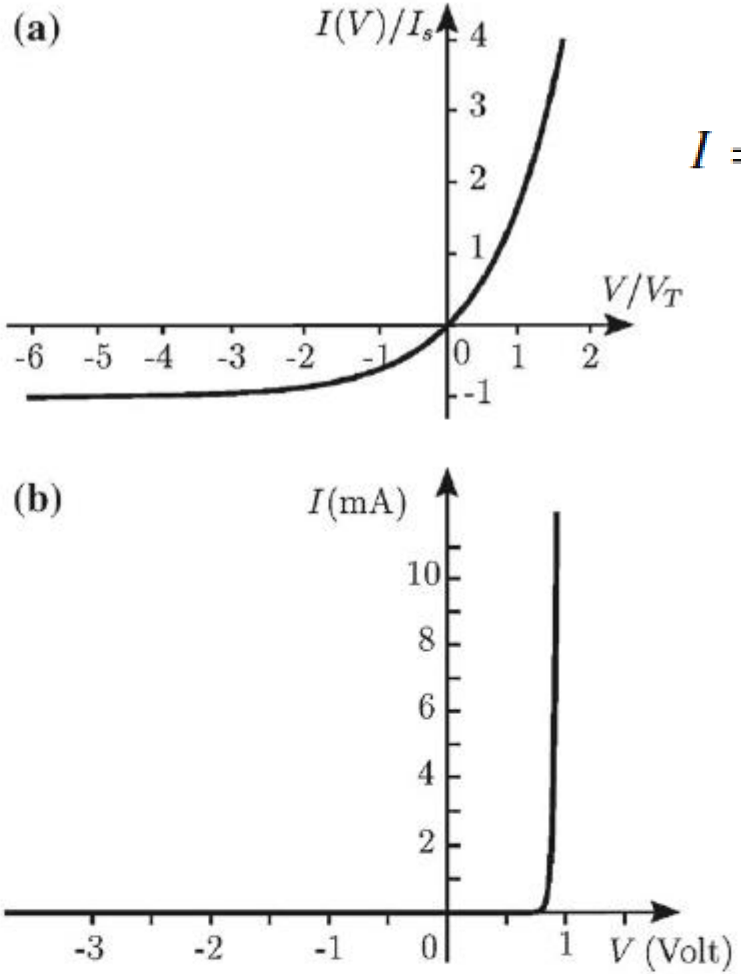
$$eV_T \equiv k_B T$$

$$I_s \approx 10^{-15} A$$

$$V_T = 25 \text{ mV}$$

$$V_z \approx 1 - 200\ V$$





$$I = I_s\left(e^{V/V_T} - 1\right)$$

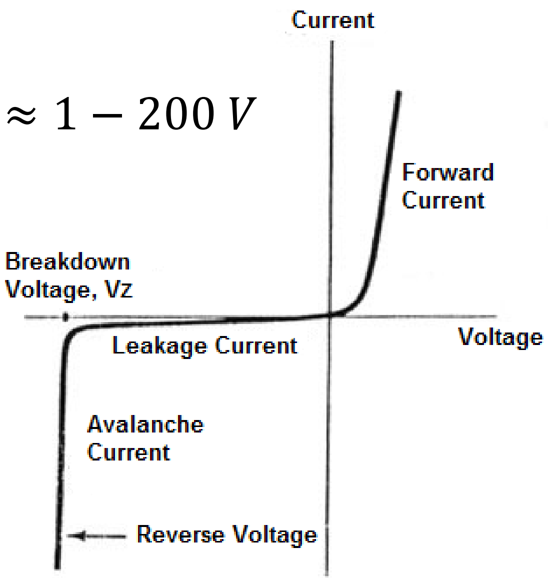
$$eV_T \equiv k_B T$$

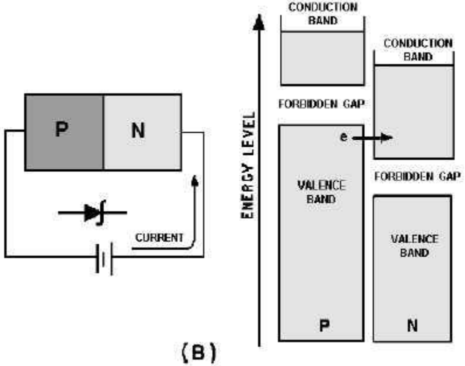
$$I_s \approx 10^{-15} A$$

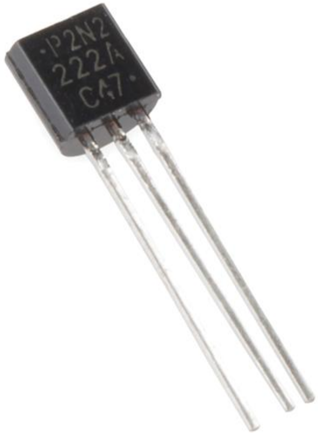
$$V_T = 25\ \text{mV}$$

Zener Diode I-V Characteristics Curve

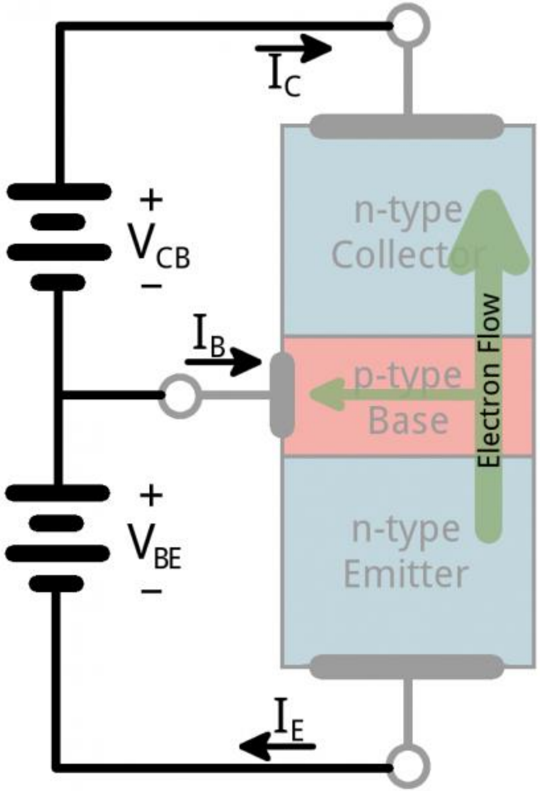
$$V_z \approx 1 - 200\ V$$



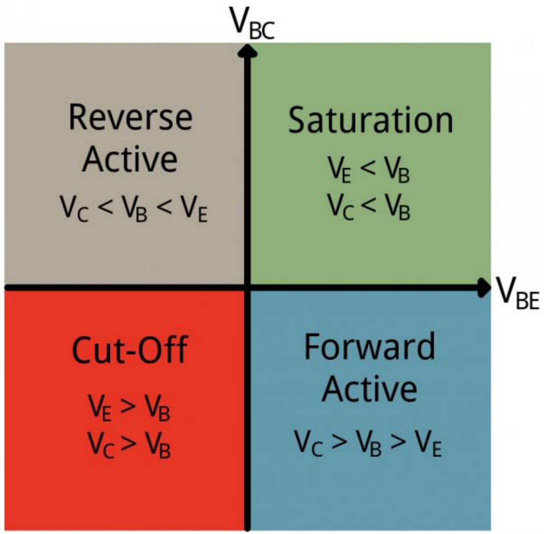




P2N2
222A
C47



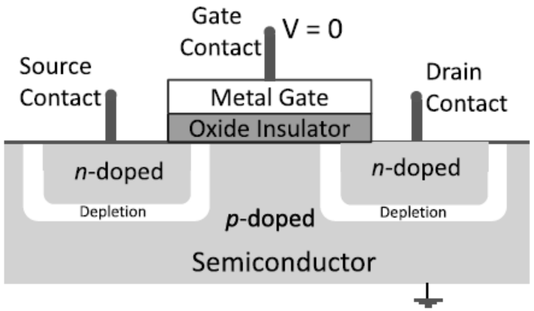
I_C
+
V_{CB}
–
I_B
+
V_{BE}
–
I_E
n-type
Collector
p-type
Base
n-type
Emitter
Electron Flow

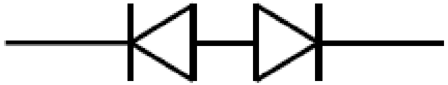


V_{BC}
V_{BE}
Reverse Active
$V_C < V_B < V_E$
Saturation
$V_E < V_B$
$V_C < V_B$
Cut-Off
$V_E > V_B$
$V_C > V_B$
Forward Active
$V_C > V_B > V_E$

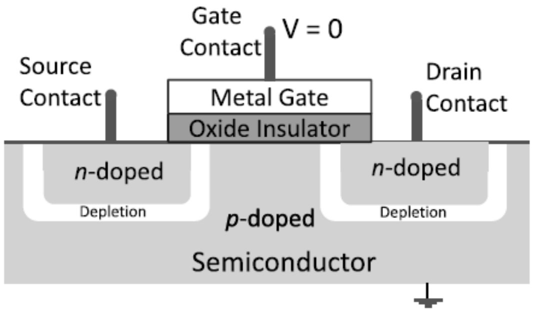
MOSFETs
(Metal Oxide Semicond. Field Effect Transistor)

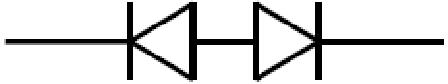
MOSFETs
(Metal Oxide Semicond. Field Effect Transistor)

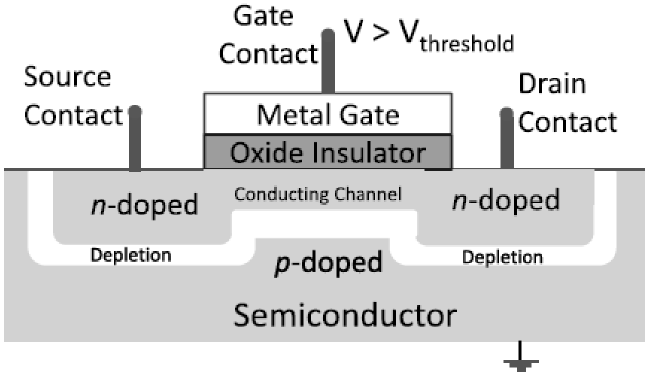




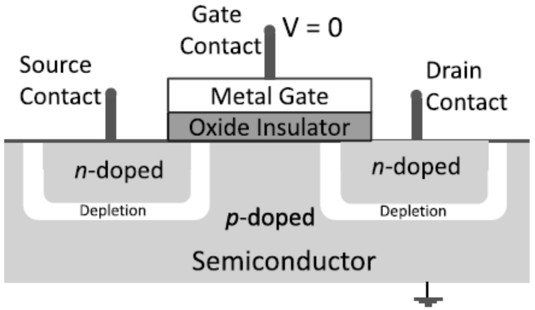
MOSFETs
(Metal Oxide Semicond. Field Effect Transistor)

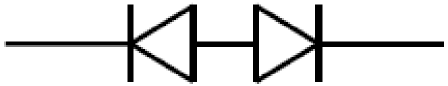


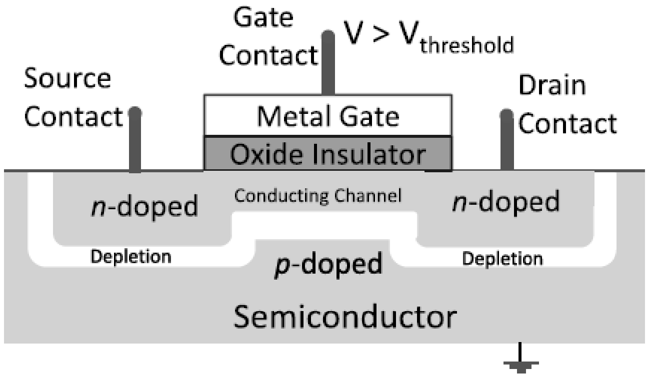




MOSFETs
(Metal Oxide Semicond. Field Effect Transistor)

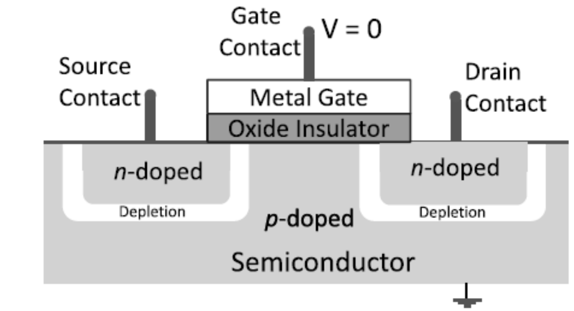


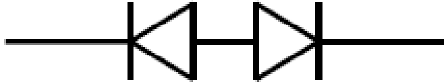


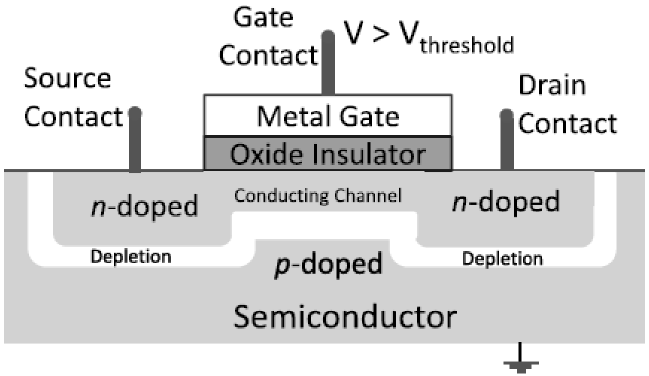


HEMTs
(High Electron Mobility Transistors)

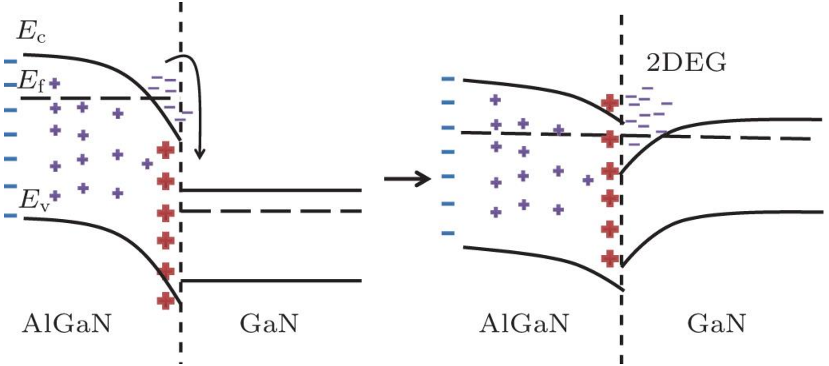
MOSFETs
(Metal Oxide Semicond. Field Effect Transistor)



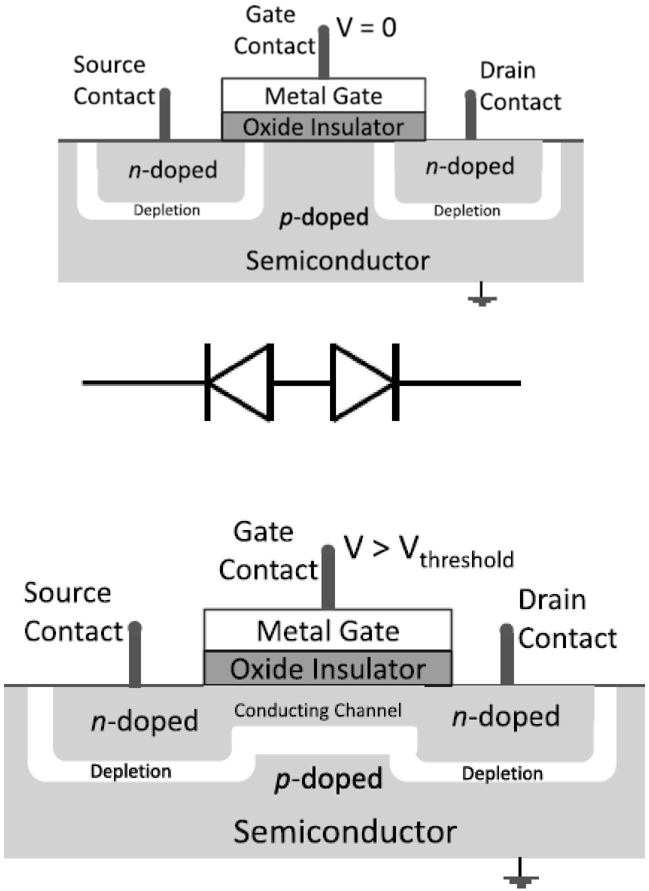




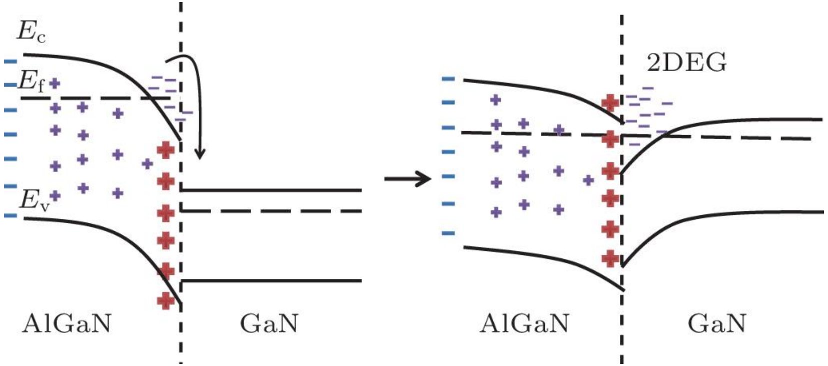
HEMTs
(High Electron Mobility Transistors)

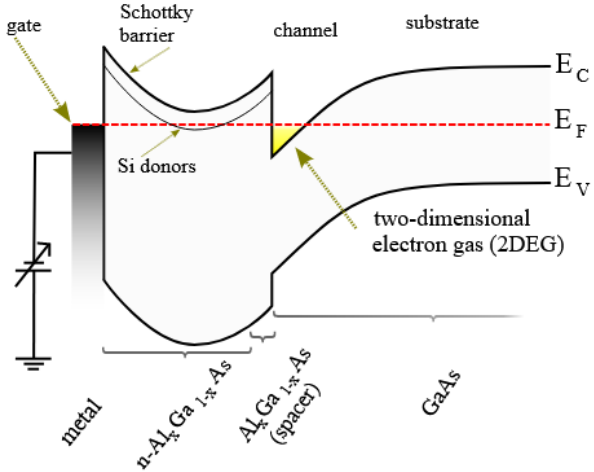


MOSFETs
(Metal Oxide Semicond. Field Effect Transistor)

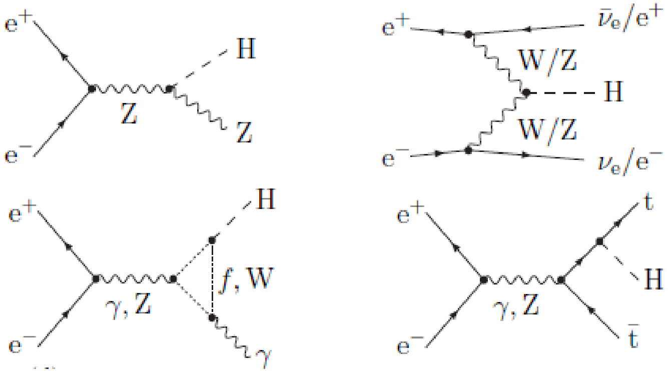


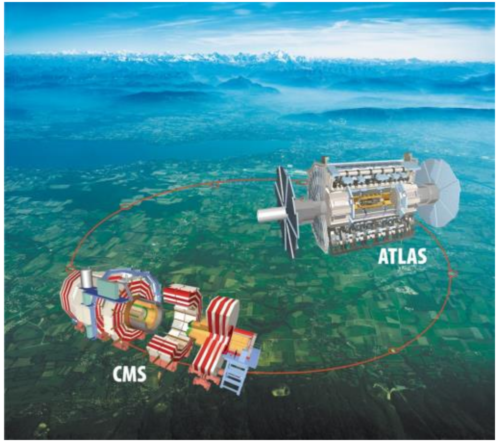
HEMTs
(High Electron Mobility Transistors)

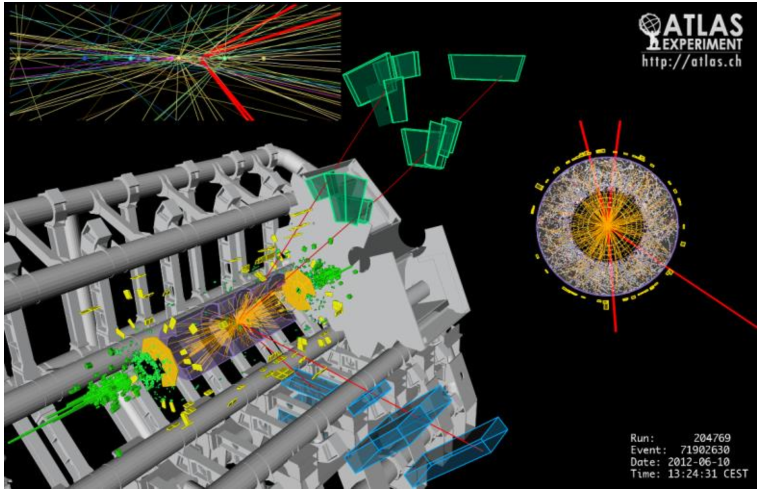


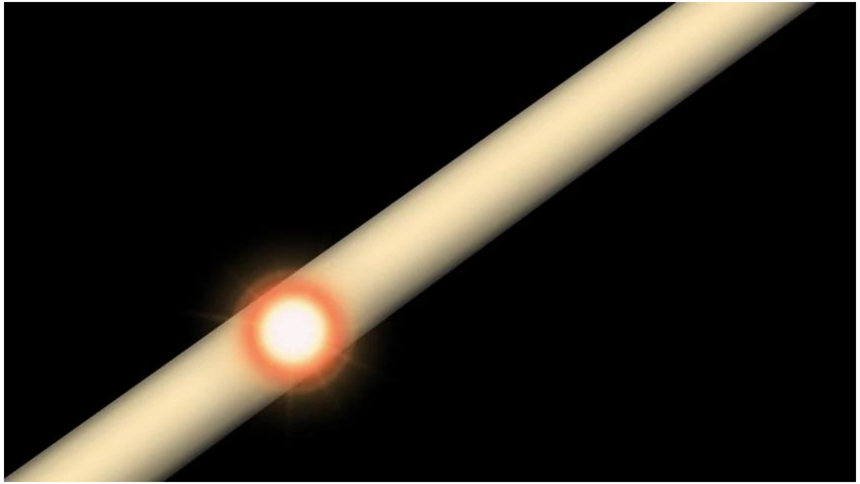


Electron-Positron collision





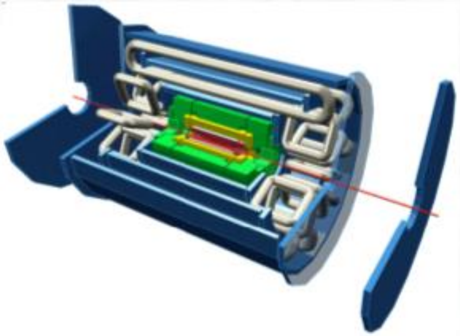


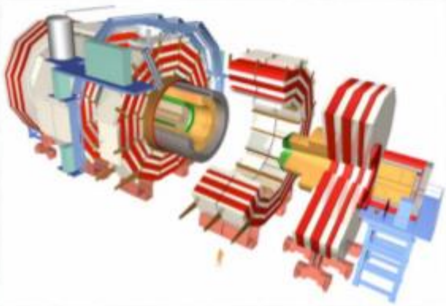


Large Hadrons Collider (LHC)

Difference between ATLAS and CMS

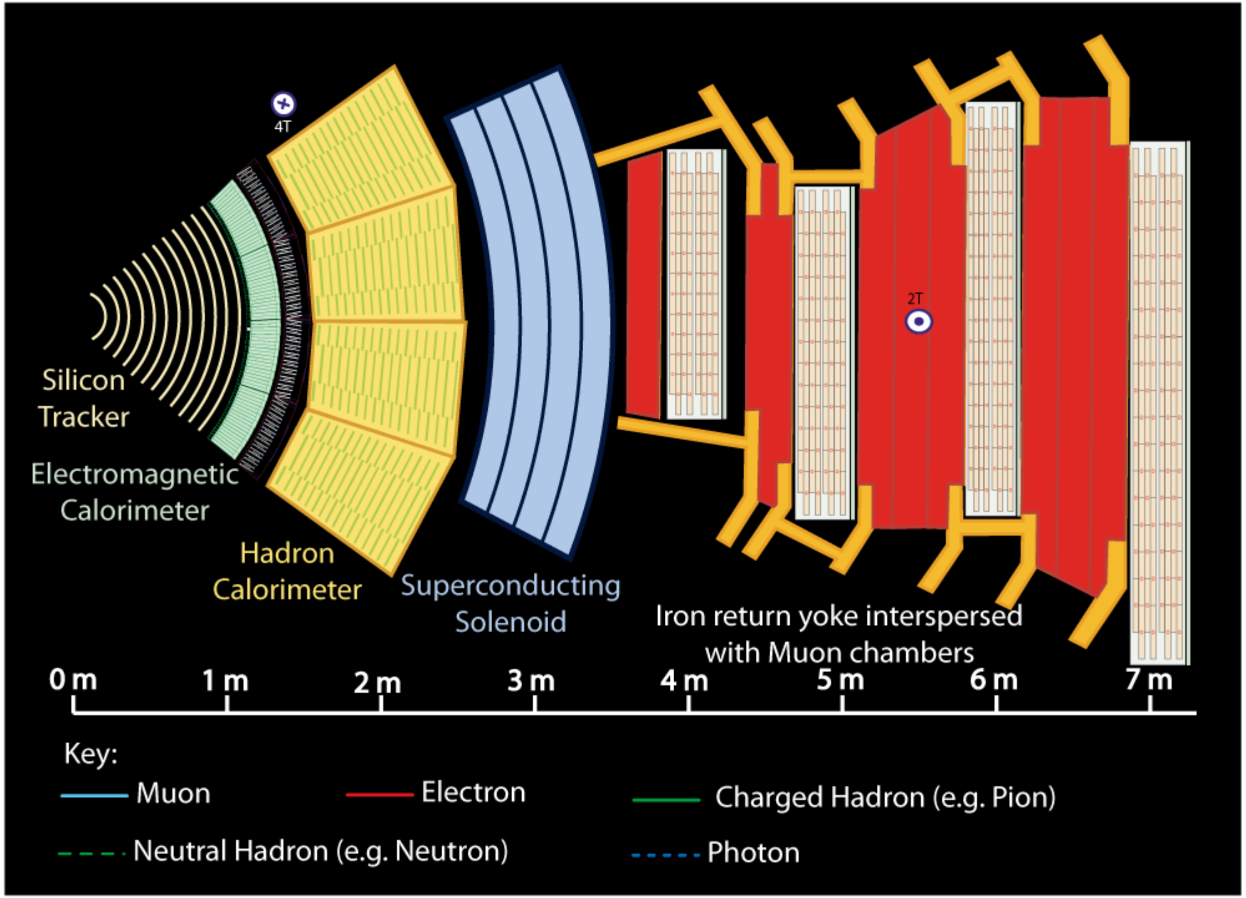
	ATLAS	CMS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)	4 T solenoid + return yoke
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$	Silicon pixels and strips (full silicon tracker) $\sigma/p_T \approx 1.5 \cdot 10^{-4} p_T + 0.005$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	$PbWO_4$ crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass + scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx$ 2% @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)	$\sigma/p_T \approx$ 1% @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)	L1 + HLT (L2 + L3)

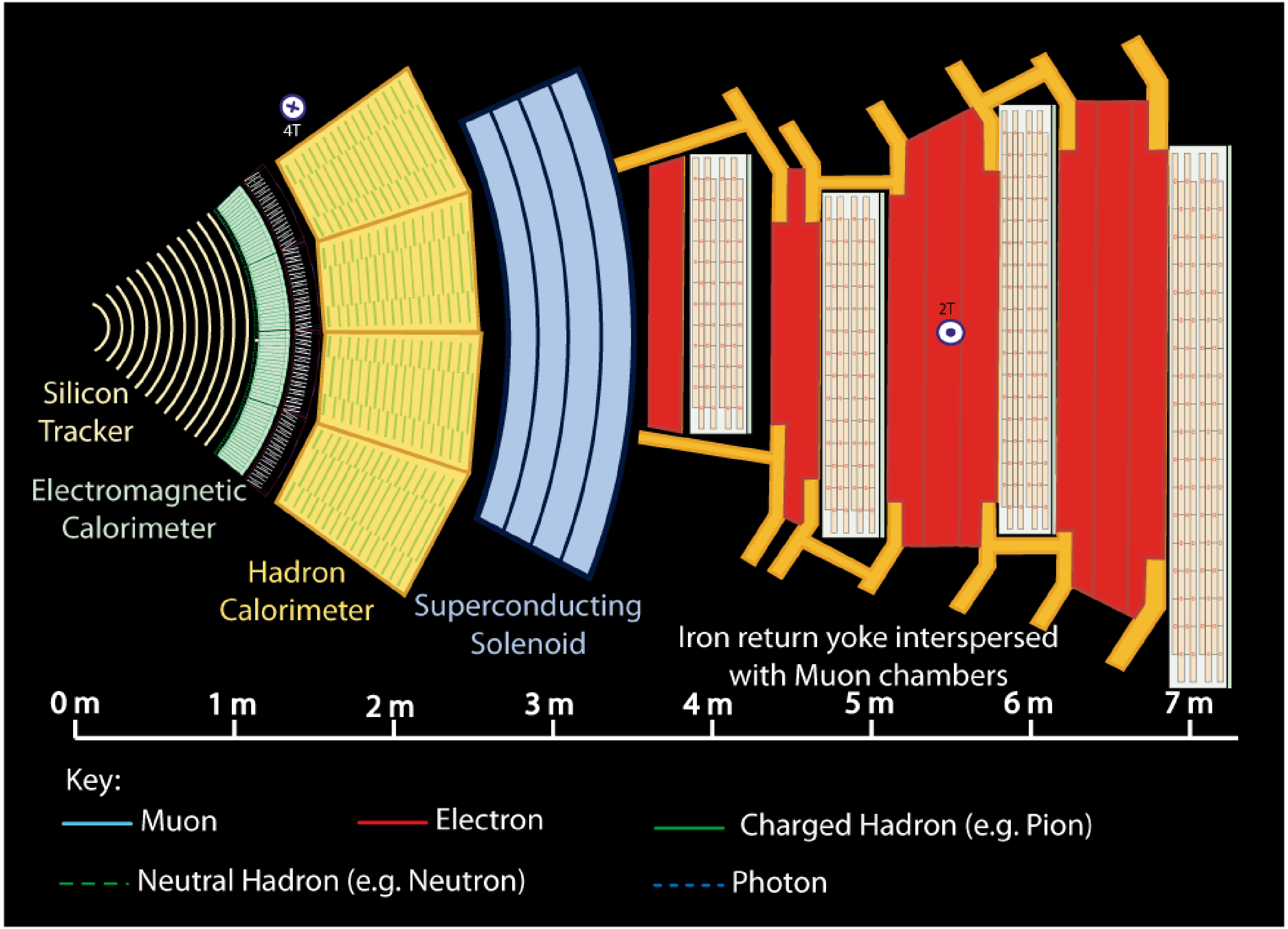




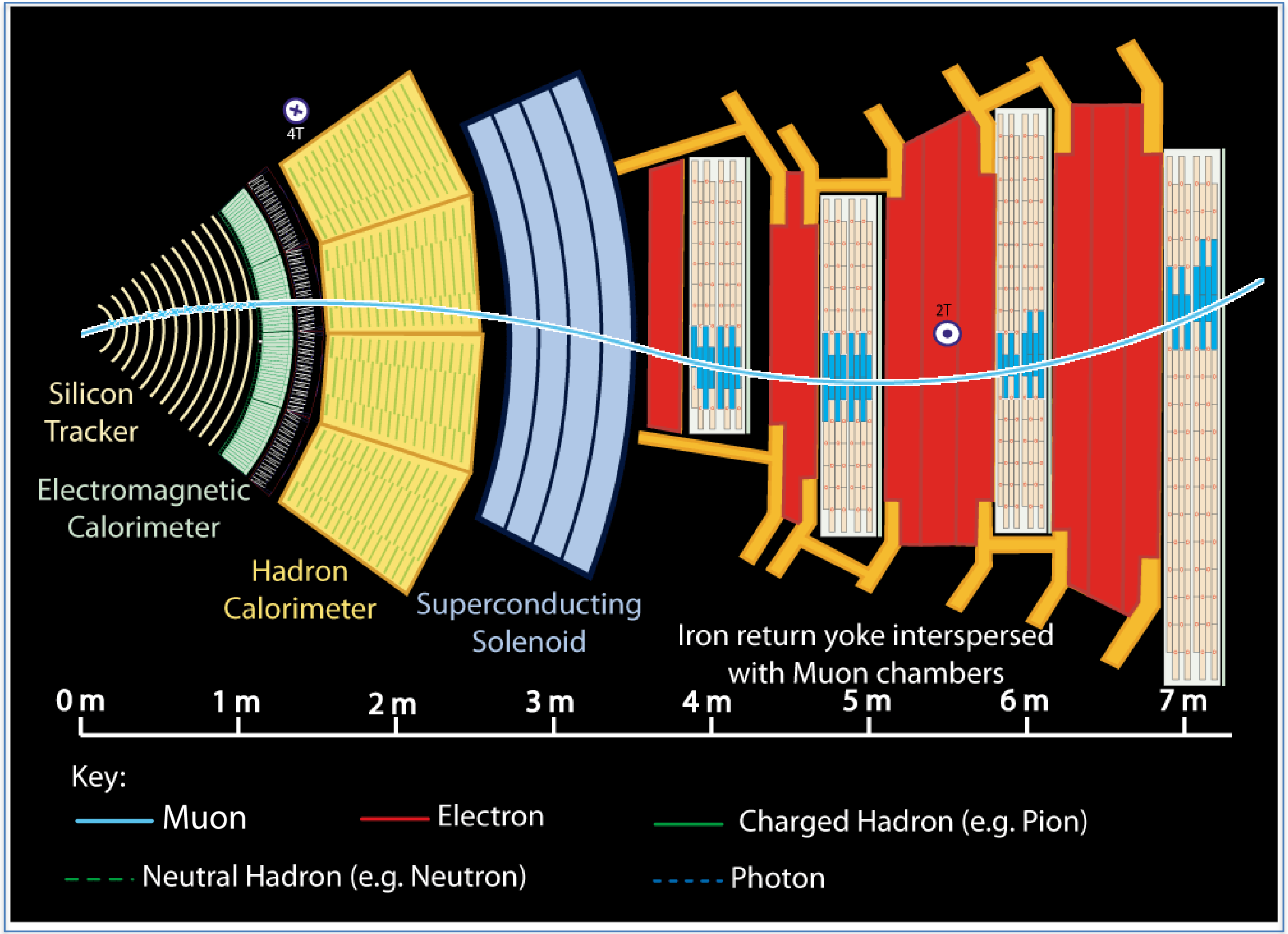
Large Hadrons Collider (LHC)

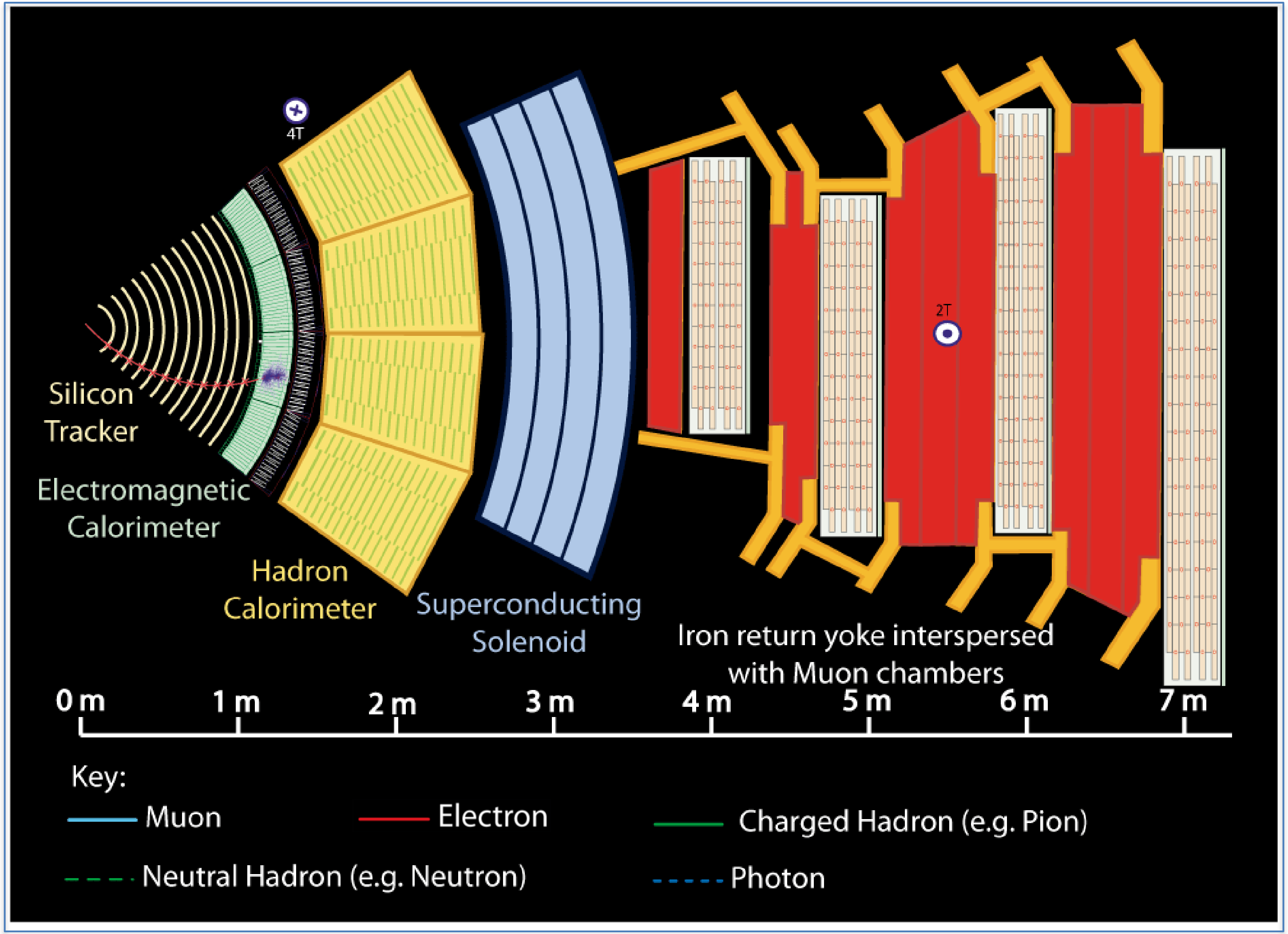
Compact Muon Solenoid (CMS)

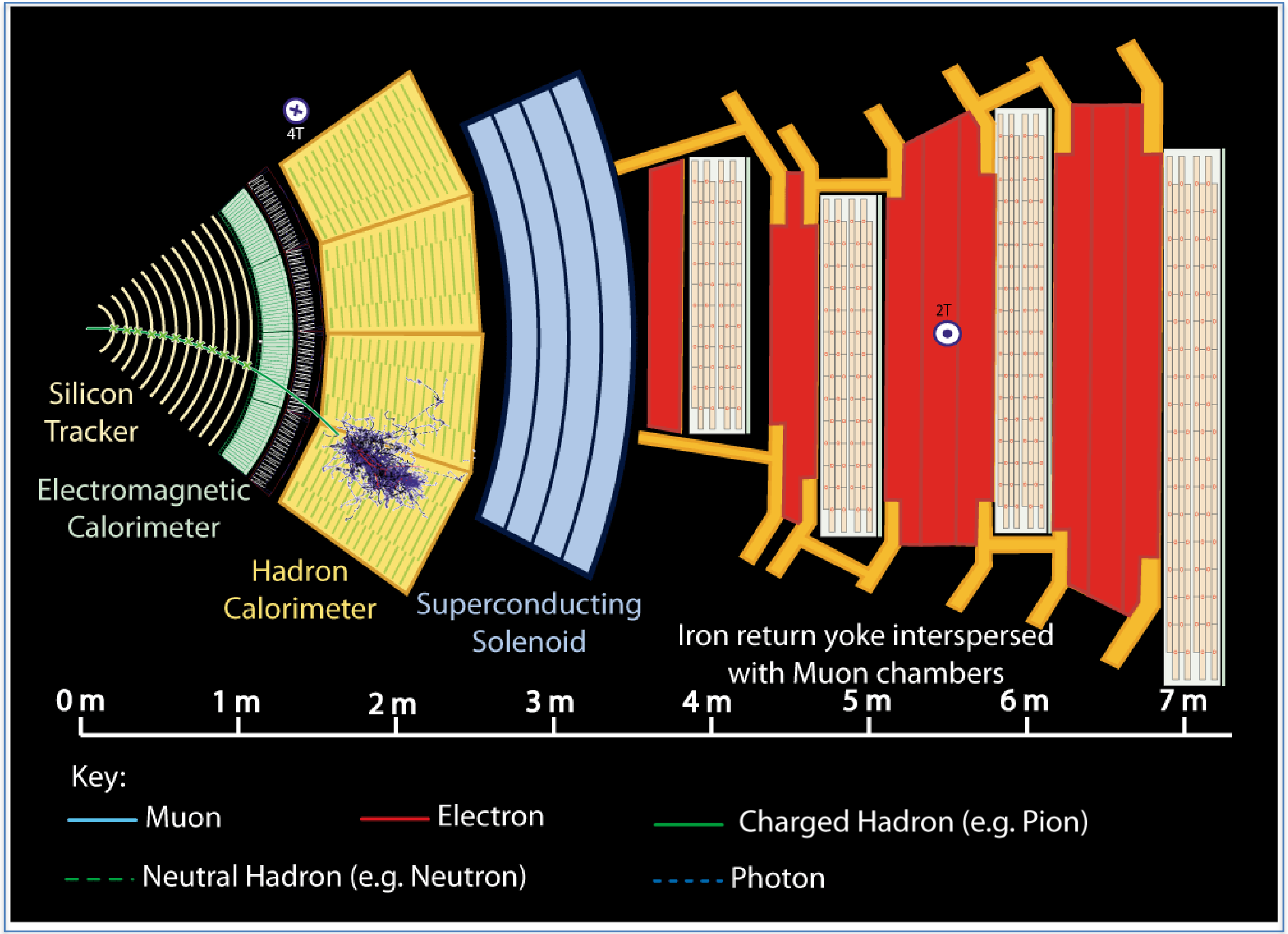


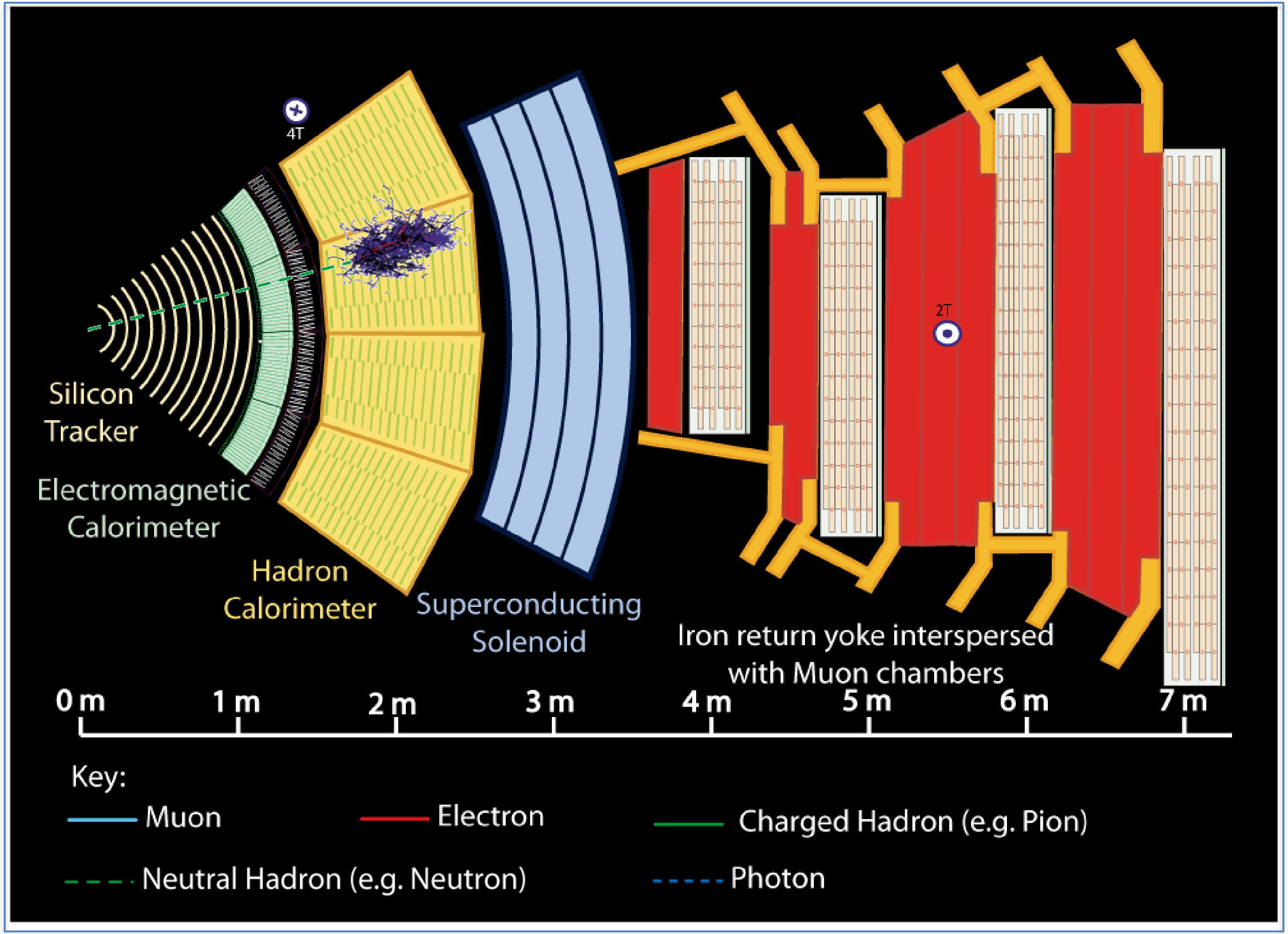


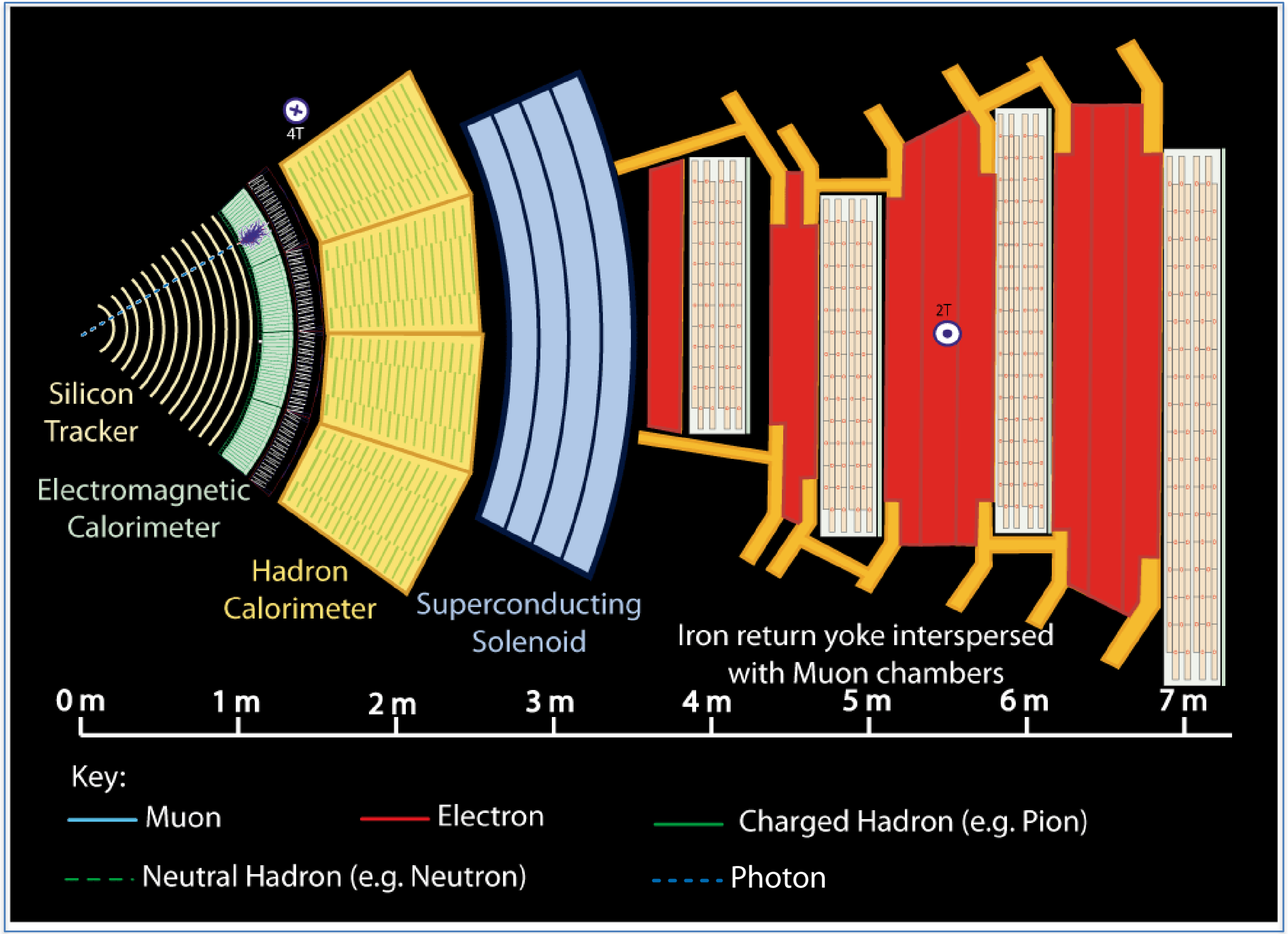
4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

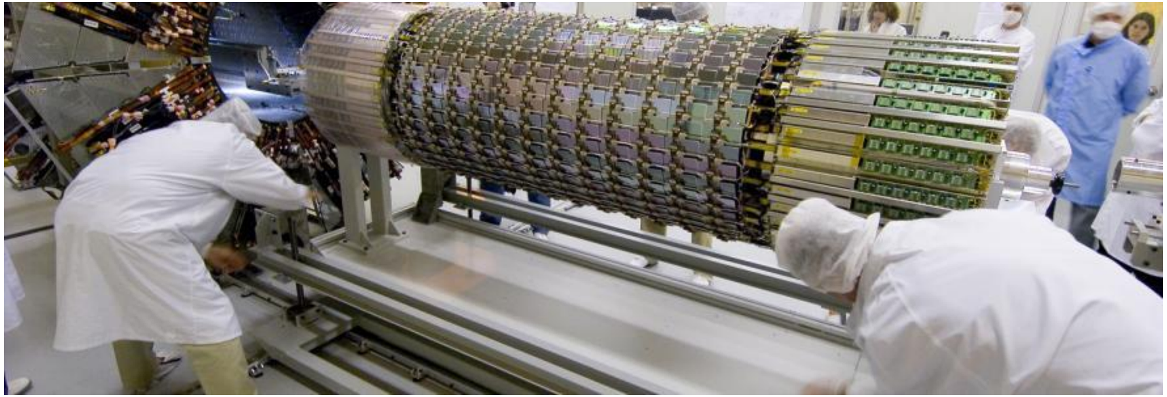

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

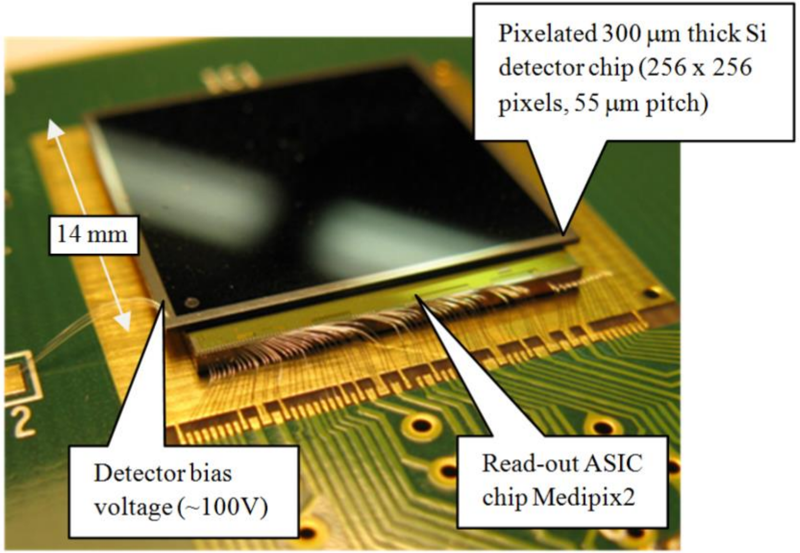

4T
Silicon
Tracker
Electromagnetic
Calorimeter
Hadron
Calorimeter
Superconducting
Solenoid
2T
Iron return yoke interspersed
with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

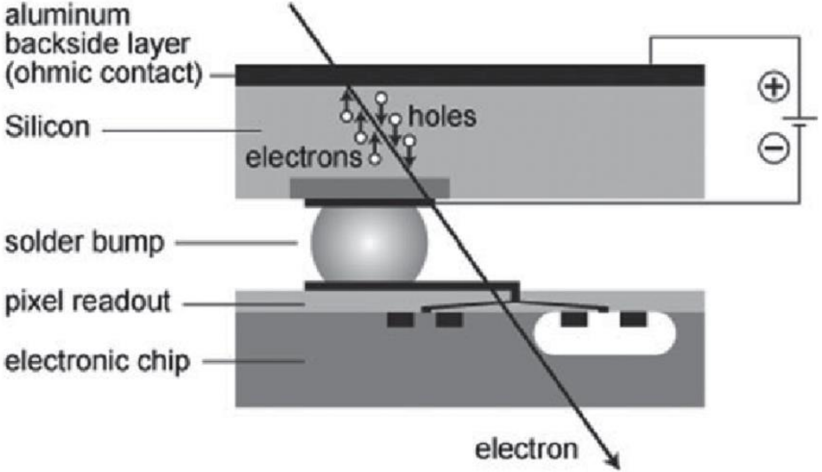

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon





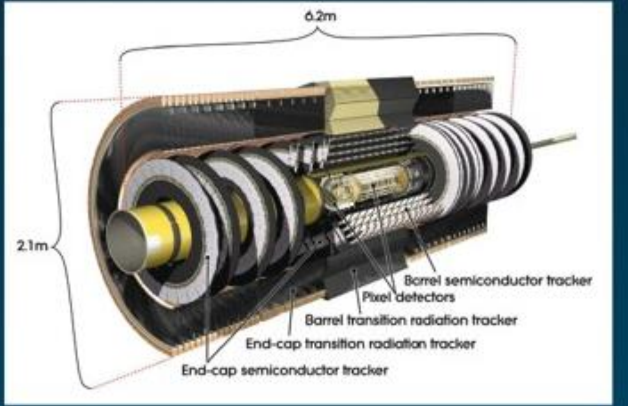
Pixelated 300 μm thick Si detector chip (256 x 256 pixels, 55 μm pitch)
14 mm
Detector bias voltage (~100V)
Read-out ASIC chip Medipix2



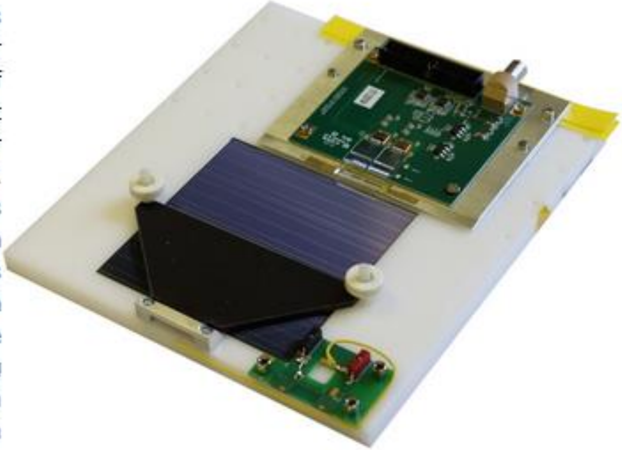
aluminum backside layer (ohmic contact)
Silicon
holes
electrons
solder bump
pixel readout
electronic chip
electron

SCT

Prototype of the ATLAS Semi-Conductor Tracker (SCT). The SCT is used to detect and reconstruct the tracks of charged particles produced during collisions. It consists of 4,088 modules of silicon covering a surface of about 62 m^2 and has over 6 million readout channels. Its layout has been optimised such that each particle crosses at least 4 layers of silicon, yielding an excellent spatial resolution of 25 μm, about 3 times thinner than a human hair.

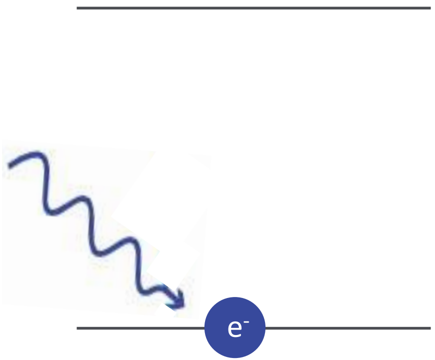


The ATLAS tracker is made up of two parts: the semiconductor tracker (SCT) and the transition radiation tracker (TRT). Together with the pixel detector at the heart of the detector, these trackers work to precisely measure the paths of particles that result from the enormously energetic particle collisions that take place at the interaction point in the centre of the detector.



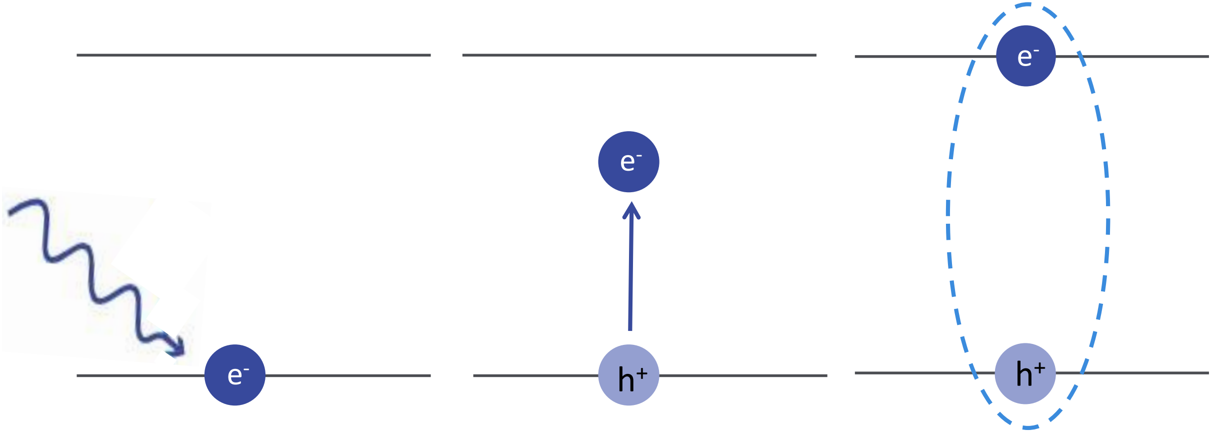
Around 700 million collisions can be detected by the tracker every second. This amount of data is far greater than what can be processed, stored or analysed by the experiment. Data from the tracker is therefore very important in working out which collisions are interesting and worth keeping and which can be discarded as uninteresting 'background' events. As a result, fewer than one in a million collisions detected in the tracker are ever actually recorded to disc for later analysis.

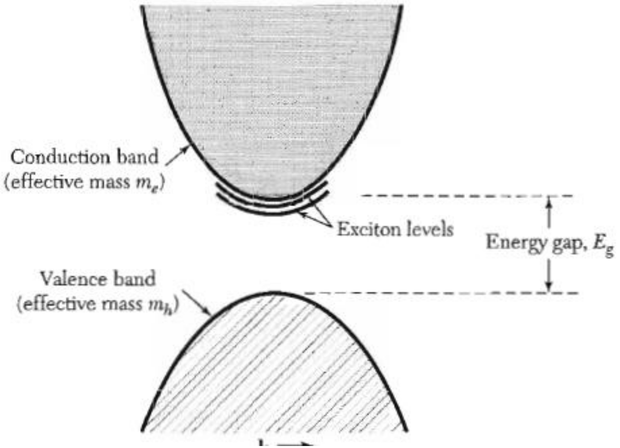
Excitons



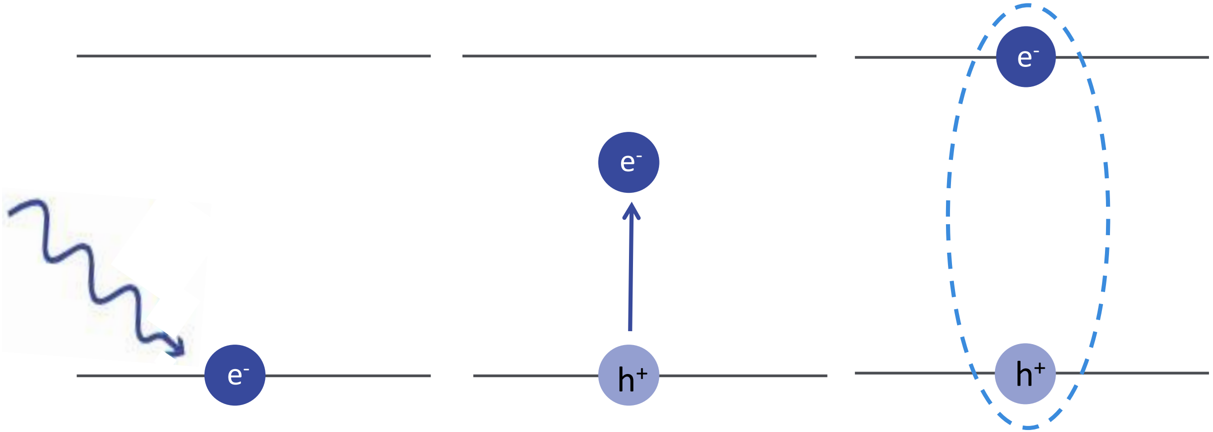
Excitons

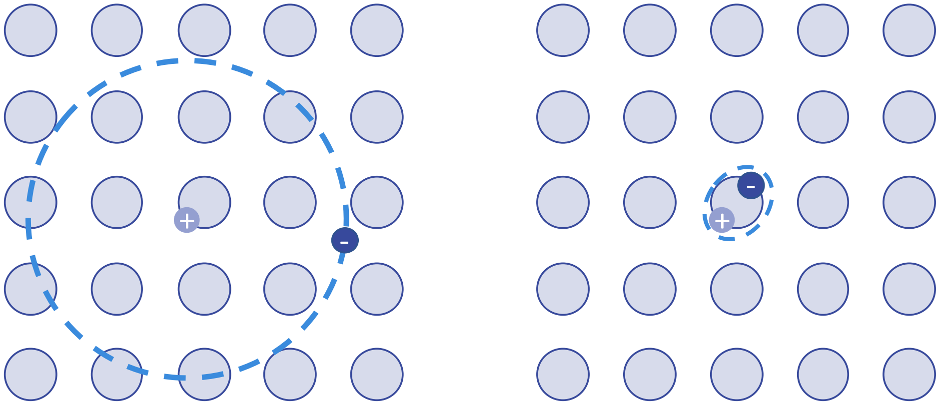
Excitons


e-
e-
h+
e-
h+


Conduction band
(effective mass m_e)
Exciton levels
Energy gap, E_g
Valence band
(effective mass m_h)

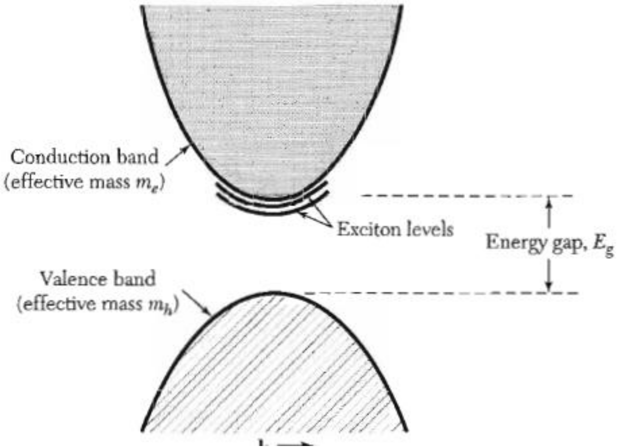
Excitons



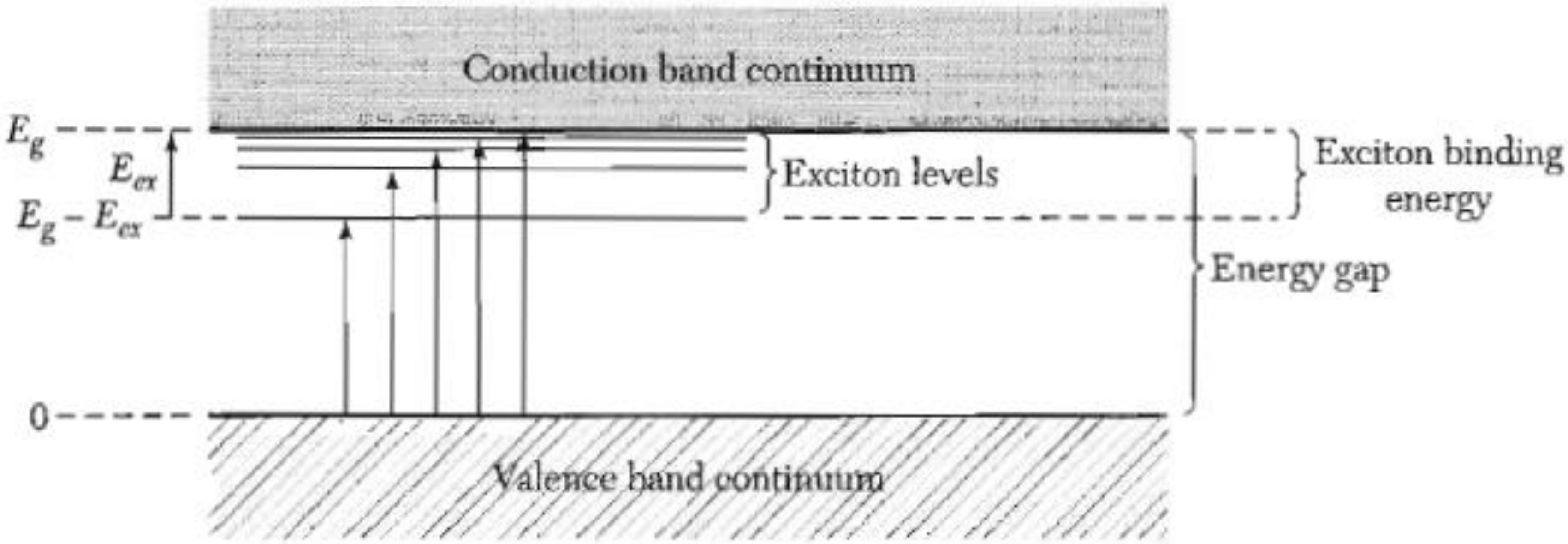


Wannier-Mott

Frenkel



Excitons



Conduction band continuum
E_g
E_{ex}
$E_g - E_{ex}$
0
Exciton levels
Exciton binding energy
Energy gap
Valence band continuum

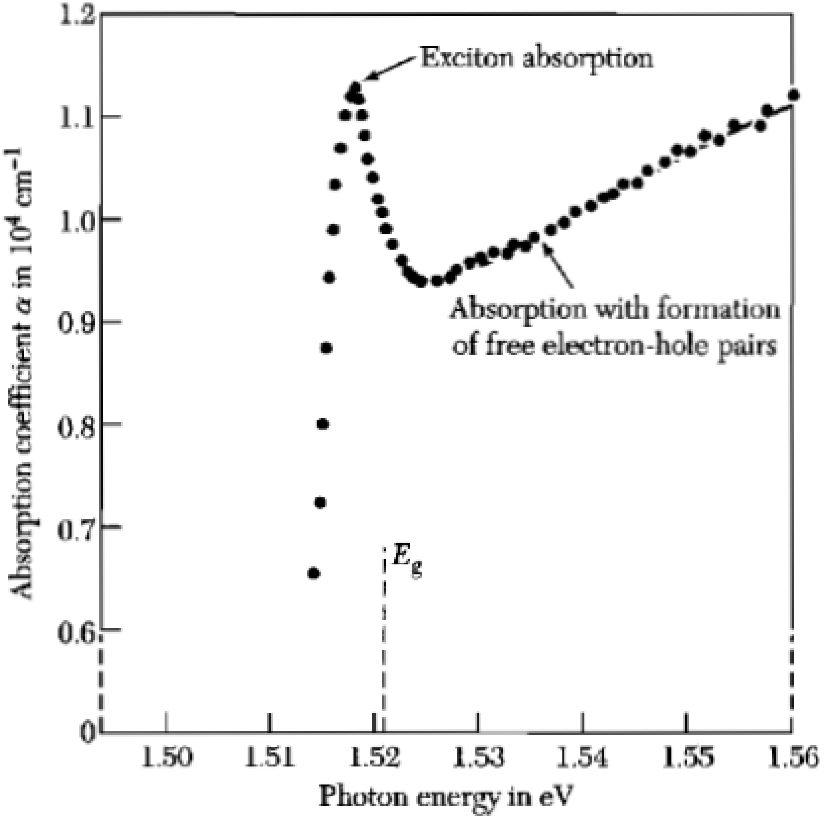
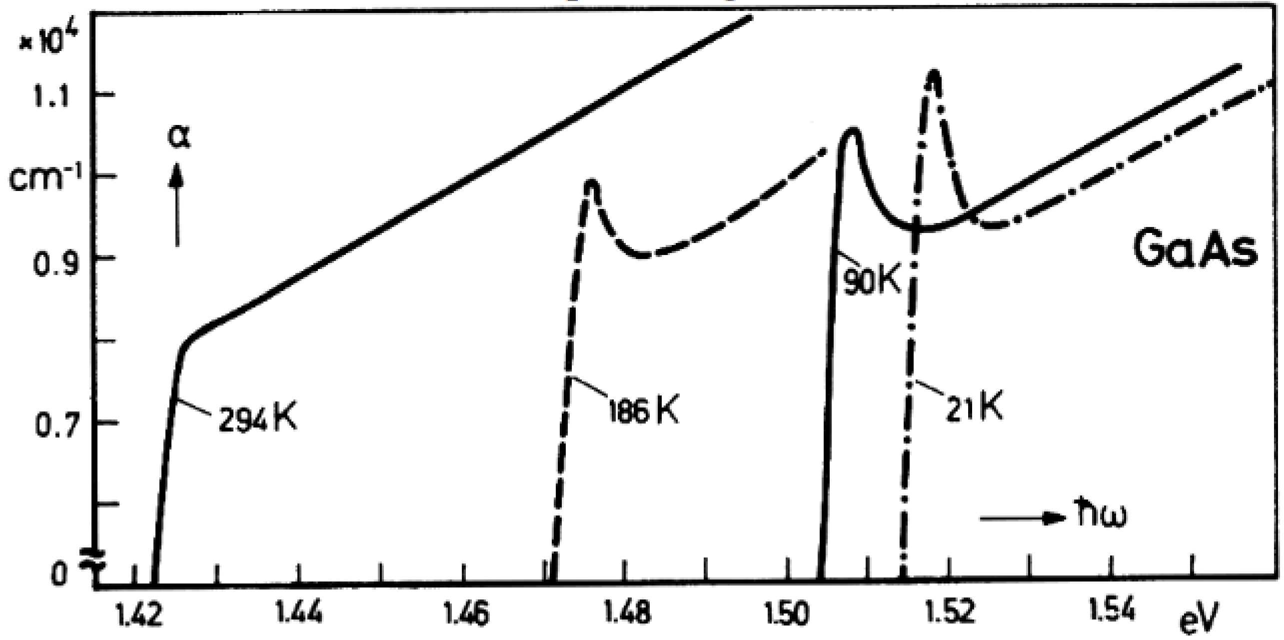
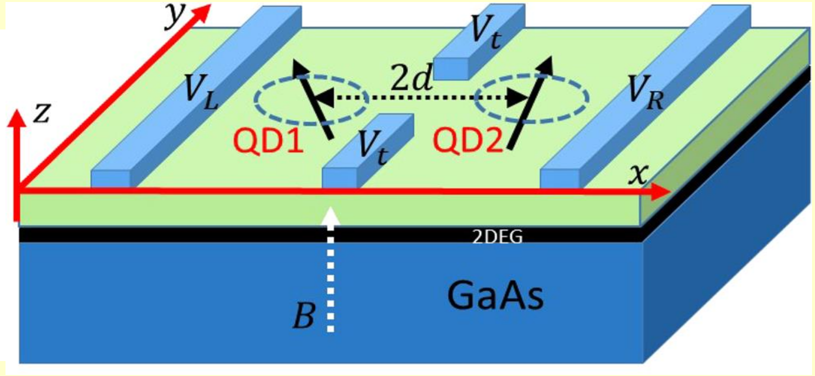


Figure 7 Effect of an exciton level on the optical absorption of a semiconductor for photons of energy near the band gap E_g in gallium arsenide at 21 K. The vertical scale is the intensity absorption coefficient α, as in $I(x) = I_0 \exp(-\alpha x)$. The energy gap and exciton binding energy are deduced from the shape of the absorption curve: the gap E_g is 1.521 eV and the exciton binding energy is 0.0034 eV. (After M. D. Sturge.)

Exciton absorption edge in GaAs





GaAs quantum dots

Loss and DiVincenzo

Phys. Rev. A (1998).