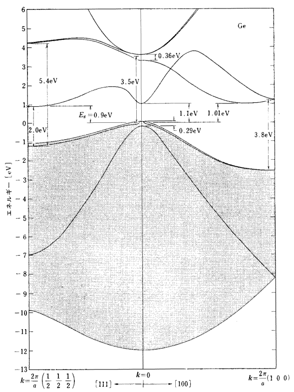
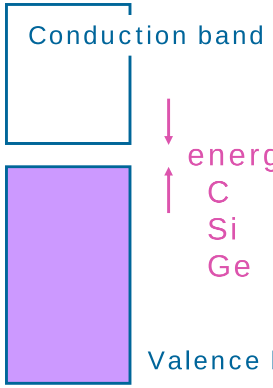
Semiconductor and the energy bands



Ge



energy gap

C 5.47 eV

Si 1.12 eV

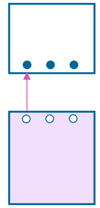
Ge 0.66 eV

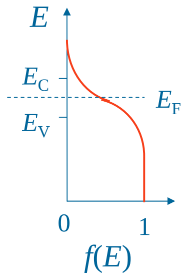
Fermi-Dirac distribution

at $E_C - E_F >> k_B T$

$$f(E) = \frac{1}{e^{\frac{E_i-\mu}{k_B T}} + 1} \rightarrow e^{-\frac{E_i-\mu}{k_B T}}$$

→ Boltzmann distribution





states density

electron number $N_e = \int D(E)\, f(E)\, dE = N_e^0 e^{-\frac{E_C - E_F}{k_B T}}$

hole number $N_p = N_p^0 e^{\frac{E_V - E_F}{k_B T}}$

$$\rightarrow N_e \cdot N_p = N_e^0 N_p^0 e^{\frac{E_V-E_F}{k_B T} - \frac{E_C - E_F}{k_B T}} = N_e^0 N_p^0 e^{-\frac{E_g}{k_B T}} \qquad E_g = E_C - E_V$$

At T, E_g=const. → hole # ↓ → E_F ↑ → electron# ↑

intrinsic sumiconductor : $N_e = N_p$ → if $N_e^0 = N_p^0$ $E_F - E_V = E_C - E_F$ →

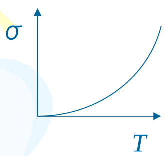
$$E_F = \left(\frac{E_C + E_V}{2} \right)$$

The Fermi level is located at the center of the energy gap.

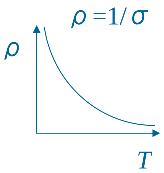
$$N_e = N_p = \sqrt{N_e^0 N_p^0} e^{-\frac{E_g}{2k_B T}}$$

electric conductivity $\sigma = N_e e \mu_e + N_p e \mu_p \propto e^{-\frac{E_g}{2k_B T}}$

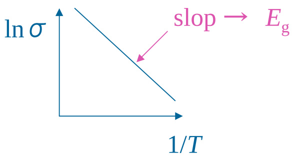
Conductivity of a semiconductor decreases at low temperatures, ∝ carrier #.



conductivity

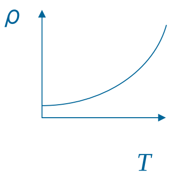


resistivity



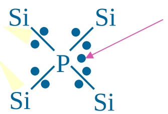
$E_a = E_g/2$ at $\sigma \propto e^{-\frac{E_a}{k_B T}}$

cf. Resistivity of a metal decreases at low temperatures, ∝ thermal vibration.



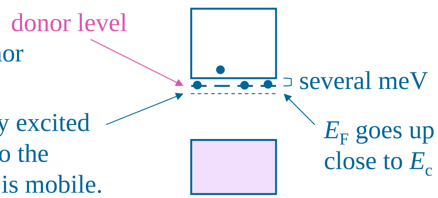
Doping

Put P, As with 5 electrons in Si : donor



Extra electron is easily excited from the donor level to the conduction band, and is mobile.

→ increasing σ in several orders

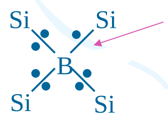


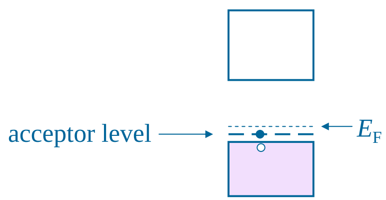
majority carrier $N_e >> N_p$ minority carrier

N-type

Negative

Put B, Al with 3 electrons in Si : acceptor



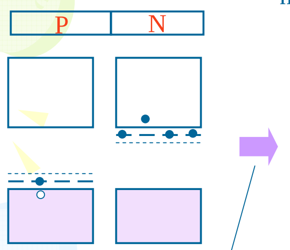


majority carrier $N_p >> N_e$ minority carrier

P-type

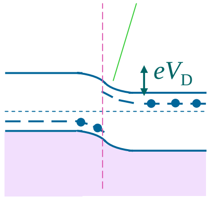
Positive

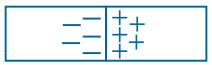
PN junction

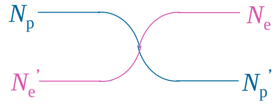


The energy bands bent so as to make E_F = const. at the junction.

Majority carrier disappears near the junction. → Depletion Layer



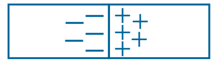




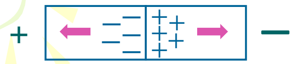
The junction polarizes opposite to the charges of the majority carriers.

No carrier.
Most resistance comes from the PN junction.

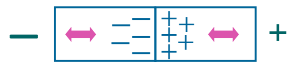
forward bias



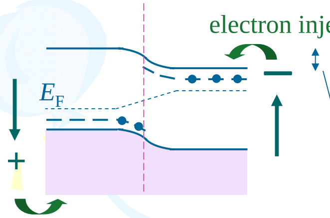
reverse bias

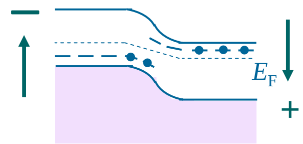


+− attracted. Current flows.



no current flows





The potential lowers to V_D-V.

Majority carrier in N region $N_e = N_e^0 e^{-\frac{E_C - E_F}{k_B T}}$

Minority carrier in P region $N_e' = N_e^0 e^{-\frac{E_C - E_F + eV_D}{k_B T}}$ ⇒ $N_e' = N_e e^{-\frac{eV_D}{k_B T}}$

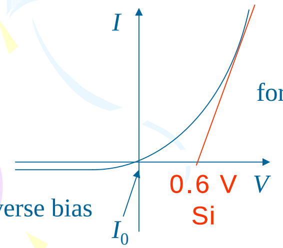
under the bias → $N_e' = N_e e^{-\frac{e(V_D - V)}{k_B T}}$

Majority carriers move from N to P (electron diffusion current) ∝ N_e

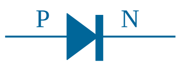
Minority carrier move from P to N (electron generation current) ∝ N_e'

total current $I \propto N_e' - N_e = I_0 (e^{eV/k_B V} - 1)$

(the same for holes)
($I_0 = N_e e^{-eV_D/k_B T}$ independent of V)



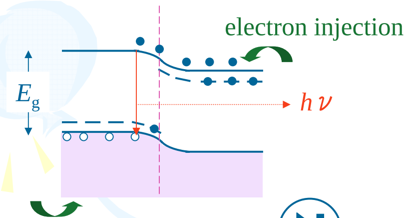
A diode passes only the forward current.

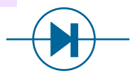


Applications of diodes

Light emitting diode

Recombination of carriers injected by the forward bias generates light.



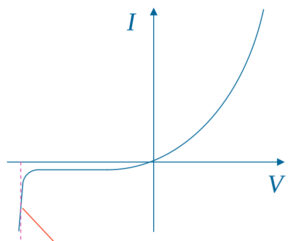


LED : Light Emitting Diode
EL : Electroluminescence

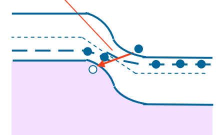
$h\nu$ depends on E_g.

Zener diode

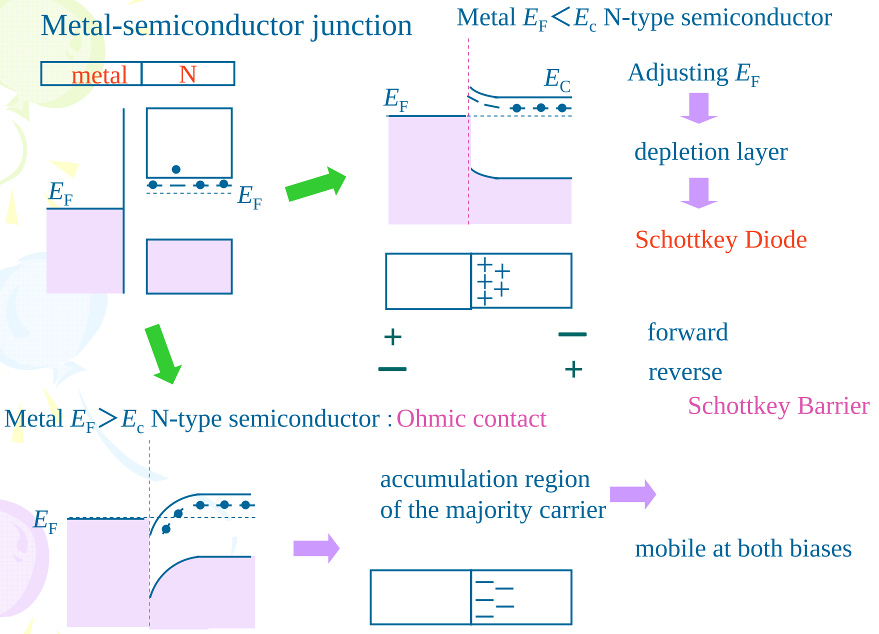
Generates standard voltage at reverse bias.



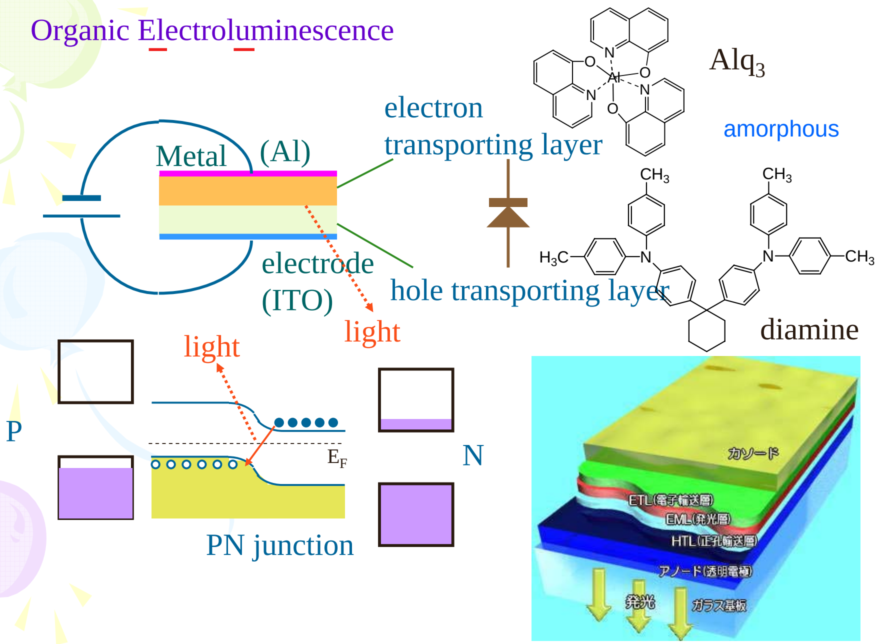
Zener Breakdown



Metal-semiconductor junction



Organic Electroluminescence



Organic EL Display

Sony 11型 2007

Mobile phone

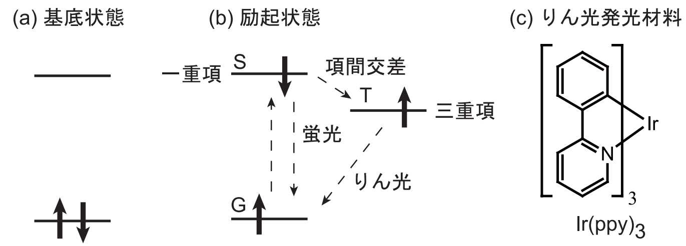
Car audio

自発光 → large contrast

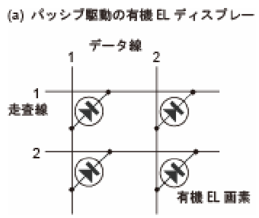
1987 Tang

発光材料

fluorescence	1/4
phosphorescence	3/4

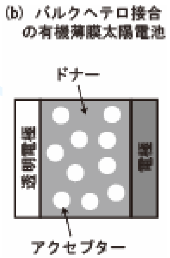


Organic EL array → display



有機ELを逆に動かせば有機太陽電池

organic photovoltaic cell

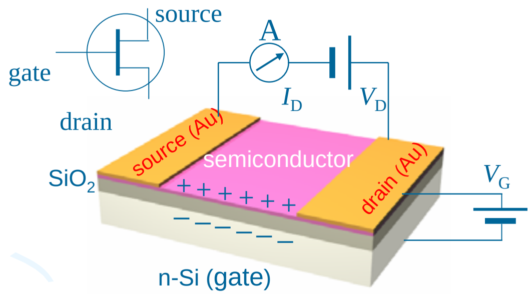


ただしキャリアを早く分離するため、PN接合をはっきり作らず、PとNをスクランブルする
→ bulk heterojunction

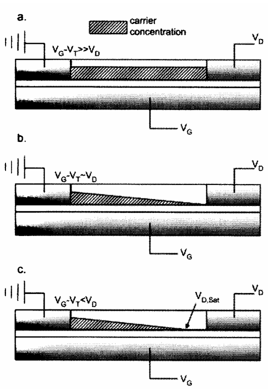
Thin film transistor

FET:Field Effect Transistor

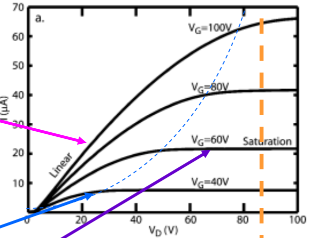
N-channel
P-channel



Thin film transistor



output characteristics



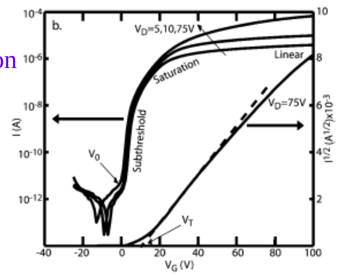
linear region

$V_G - V_T = V_D$

pinch off

saturation region

transfer characteristics



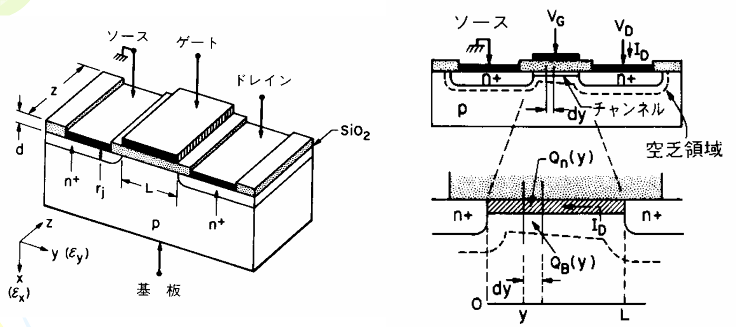
mobility

$$I_D = \frac{W\mu C}{L}\left((V_G - V_T)V_D - \frac{1}{2}V_D^2\right)$$

typically L = 50 μm, W = 1 mm

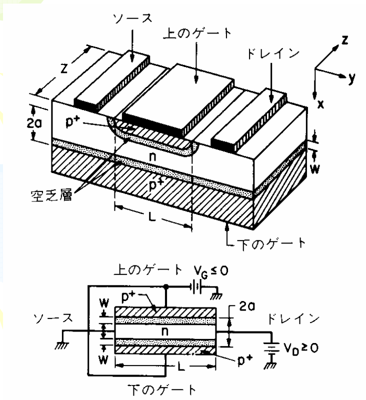
$$C = \frac{\varepsilon S}{d}$$

Single crystal FET



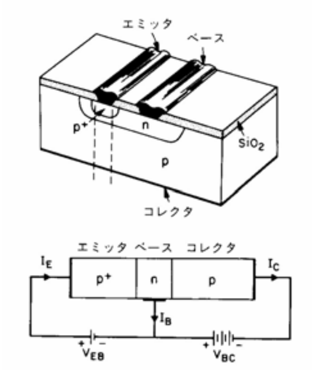
Minority carriers in MOS inverted layer carry the charge.
cf. Thin film transistor uses majority carriers.
Inversely biased PN junction either at source or at drain.
(off current)
cf. Thin film transistor uses ohmic contacts.

Junction FET



Inversely biased pn junction provides the gate electrode.

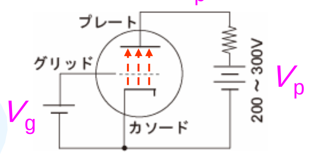
Bipolar transistor

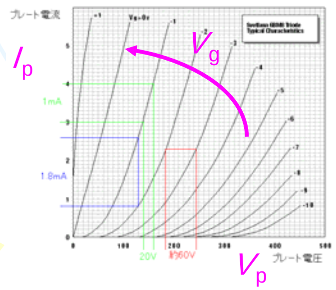


PNP junction
minority carriers pass
the thin base.

Three-terminal devices

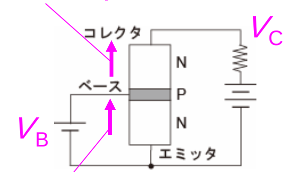
真空管





Junction transistor

Since B is thin,
current passed to C, I_C



EB: forward bias

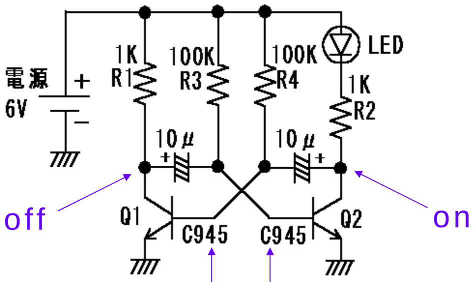
V_B high I_c high V_c low

V_B low I_c low V_c high

V_B on → V_c off

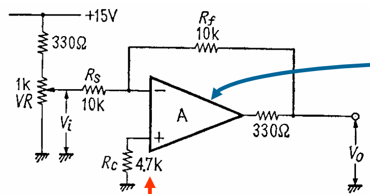
V_B off → V_c on

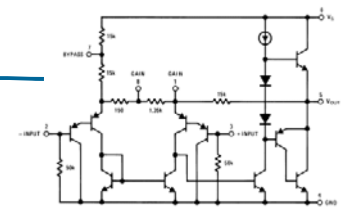
Flip Flop



トランジスタ回路の設計はバイアスが面倒

Operational amplifiers (OP-amp) provide ideal analog amps.





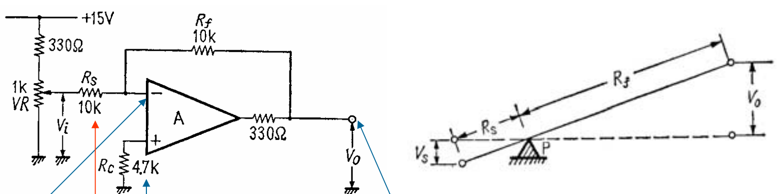
反転入力－と非反転入力＋の
電圧は必ず等しい

Always inputs + and –
have the same voltage.

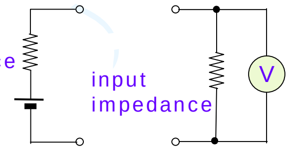
ほぼ理想的なアナログアンプ

アナログ回路はオペレーションアンプ(OPアンプ)でできる

Most analog circuits are realized by OP-amps.

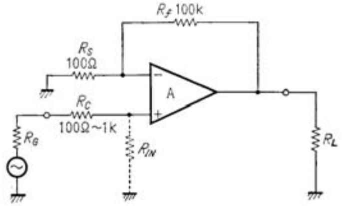


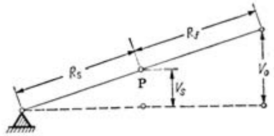
$$V_0 = -\frac{R_f}{R_s} V_i$$



反転増幅回路

非反転増幅回路

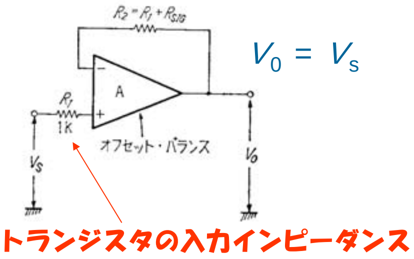




$$V_0 = \frac{R_s + R_f}{R_s} V_s$$

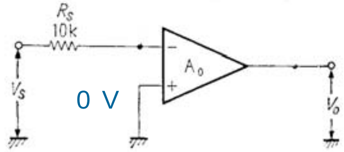
ヴォルテージフォロワ

入力インピーダンスを稼ぐ非反転増幅回路



$V_0 = V_s$

コンパレータ



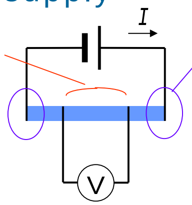
$V_s > 0 \rightarrow V_0 = -V_c$ 電源電圧

$V_s < 0 \rightarrow V_0 = V_c$

Resistance measurements by the four-probe method

current supply

$$R = \frac{V}{I}$$



cancel the contact resistance

The voltmeter has infinite input impedance?

反転増幅回路：入力抵抗　100 kΩ

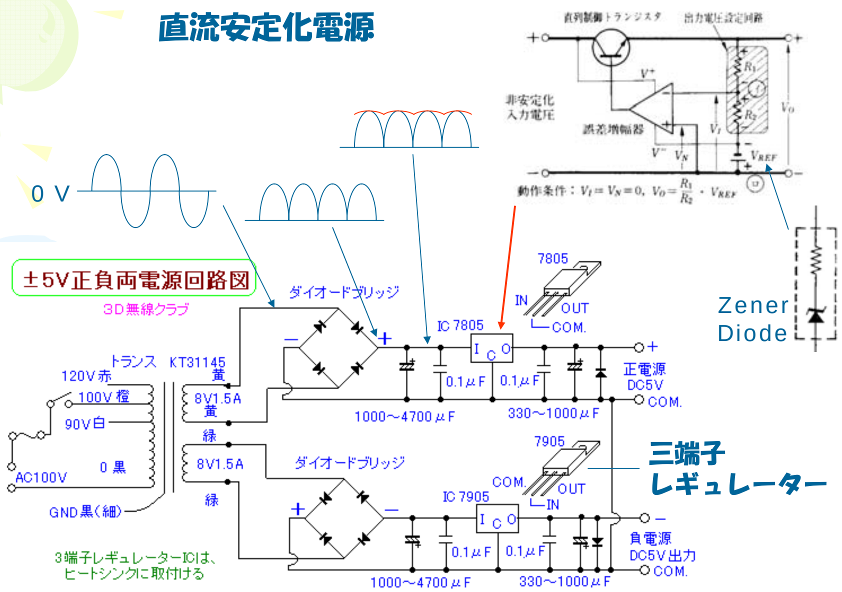
非反転増幅回路：トランジスタ

接合型トランジスタ　　1 MΩ以下

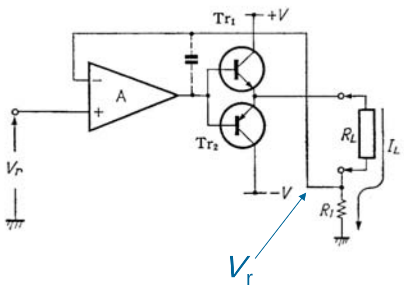
電界効果トランジスタ　非常に高い

通常の電圧計の入力インピーダンスは10 MΩ以下

直流安定化電源



定電流回路



$$I_L = \frac{V_r}{R_1}$$

有機エレクトロニクス

カラーディスプレイ

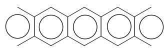
電解
コンデンサー

LED素子

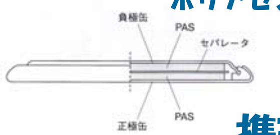
2次電池

導電性高分子の応用

1. 2次電池（バックアップ電源）

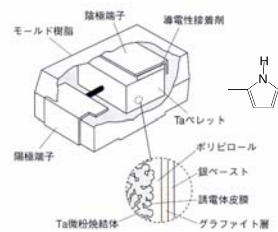


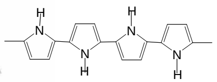
ポリアセン系



携帯電話

2. 電解コンデンサ





ポリピロール
高周波特性

有機トランジスタの応用

(1) フレキシブルディスプレー
→ 電子ペーパー

NHK

有機TFT駆動
有機ELパネル

(2) フレキシブルスキャナー

(3) フレキシブルセンサー

ロボットの人工皮膚

東大　染谷隆夫

有機トランジスタの応用

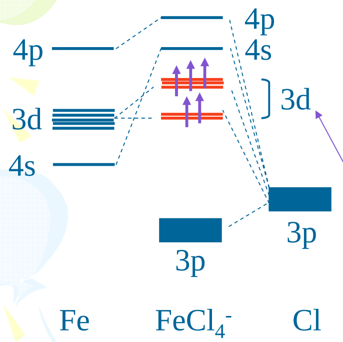
(4) 安価 → RF IDタグ

← インクジェットプリンティング

大面積
フレキシブル
安価
→
ペンキでICを

Magnetism in transition metal compounds

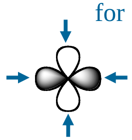
Molecular orbital of transition metal compounds:



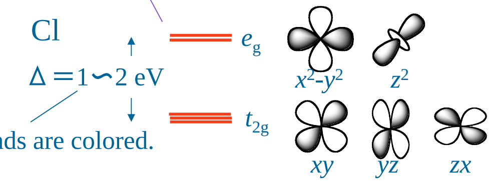
Ligand levels are bonding orbitals.
Metal d-levels are antibonding.
s,p-levels are strongly antibonding.
All valence electrons inters d-levels.

Crystal field splitting

for octahedral Oh



2 e_g orbitals are more antibonding
→ go above 3 t_{2g} orbitals.

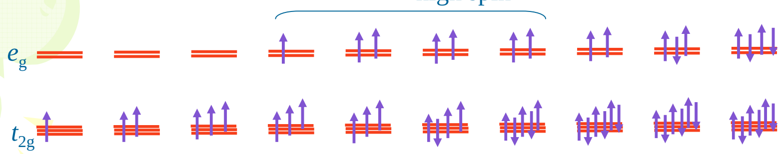


Absorb visible light.
→ Transition metal compounds are colored.

Crystal-field theory:
molecular orbital theory of transition metals

3 t_{2g} orbitals have node in the direction of the ligands.
→ no chemical bond.

Octahedral crystal field

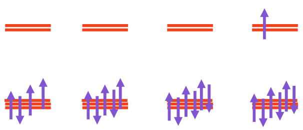


	d¹	d²	d³	d⁴	d⁵	d⁶	d⁷	d⁸	d⁹	d¹⁰
S=	1/2	1	3/2	2	5/2	2	3/2	1	1/2	0
	Ti^{3+}	Ti^{2+}	Cr^{3+}	Cr^{2+}	Fe^{3+}	Fe^{2+}	Co^{2+}	Ni^{2+}	Cu^{2+}	Zn^{2+}
	V^{4+}	V^{3+}	Mn^{4+}	Mn^{3+}	Mn^{2+}	Co^{3+}	Ni^{3+}			Cu^{+}
				Ti^0	V^0	Cr^0	Mn^0	Fe^0	Co^0	Ni^0
				4	5	6	7	8	9	10

low spin states for d=4∽7

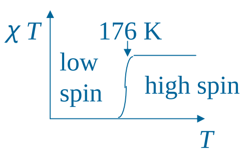
Transition from high spin to low spin states.
Spin crossover

Low spin d⁶ is non magnetic



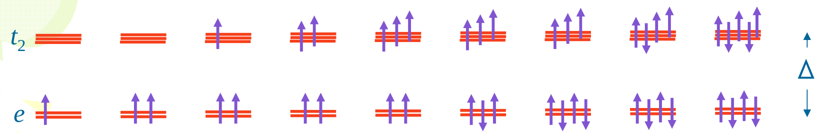
d⁴	d⁵	d⁶	d⁷
S= 1	1/2	0	1/2

[$Fe^{II}(phen)_2(NCS)_2$]



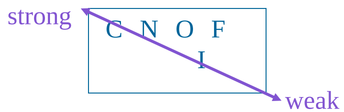
Tetrahedral crystal field

Td: upside down, always high spin



	d¹	d²	d³	d⁴	d⁵	d⁶	d⁷	d⁸	d⁹
S=	1/2	1	3/2	2	5/2	2	3/2	1	1/2

Magnitude of Δ: spectrochemical series
$I^- < Br^- < Cl^- < F^- < OH^- < H_2O$
$< NCS^-$ ∽ NH_3 < en < phen < CN^-



$FeCl_4^-$: Fe^{3+} → Fe^0 → d⁸ → 8−3 → d⁵ → S=5/2

Quiz

$MnCl_4^{2-}$ ( ) MnO_4^- ( ) $CuCl_4^{2-}$ ( )
$CoCl_4^{2-}$ ( ) $NiCl_4^{2-}$ ( ) MnO_2 ( )

$J = L + S$

orbital　　spin angular momentum

transition metal compounds　　$L \rightarrow 0$

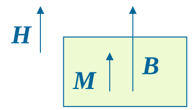
軌道角運動量の消滅

(d電子は結晶場により回転できない。)

Lanthanides　　L survives.

4f電子は内殻にあるため「回転運動」できる。

Magnetic susceptibility



External magnetic field H

→ magnetization M

物質内部の磁束密度 B: $B = \mu_0(H + M)$

$\chi = M / H$　magnetic susceptibility

Diamagnetic　without unpaired electrons

$\chi < 0$　　$B < \mu_0 H$

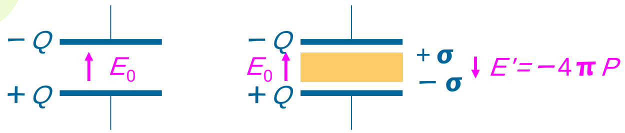
Paramagnetic　with unpaired electrons

$\chi > 0$　　$B > \mu_0 H$

However, usually　$M \lesssim 10^{-3}$

cf. Electric field

capacitor　　　with dielectrics



$Q = CV$

$C = \dfrac{\varepsilon_0 S}{d}$　$E_0 = \dfrac{V}{d}$

$E = E_0 + E' = E_0 - 4\pi P$　　$E_0 \rightarrow D$

➡ $D = E + 4\pi P$

polarization

electric displacement field

電束密度

electric field without dielectrics

actual electric field in the dielectrics (much smaller than D)

$\dfrac{D}{E} = \varepsilon = 1 + 4\pi P$　➡　E is $1/\varepsilon$ of D

In a metal, $E = 0$, and $D = 4\pi P$.

Electric field

$D = E + 4\pi P$　cgs

$D = \varepsilon_0 E + P$　MKS

external field D

actual electric field E

polarization P

Always $\varepsilon > 0$ and $P > 0$

Magnetic field

$B = H + 4\pi M$　cgs

$B = \mu_0 H + M$　MKS

external field H

actual magnetic field B

magnetization $M > 0$

$P > 0$ corresponds to $M < 0$ (diamagnetic).

However,

Dielectrics:　V in a capacitor controls　$E = D - 4\pi P$

Magnet:　I in a coil controls　$H = B - 4\pi M$