박막및나노표면공학-강의자료

제2장 전기도금

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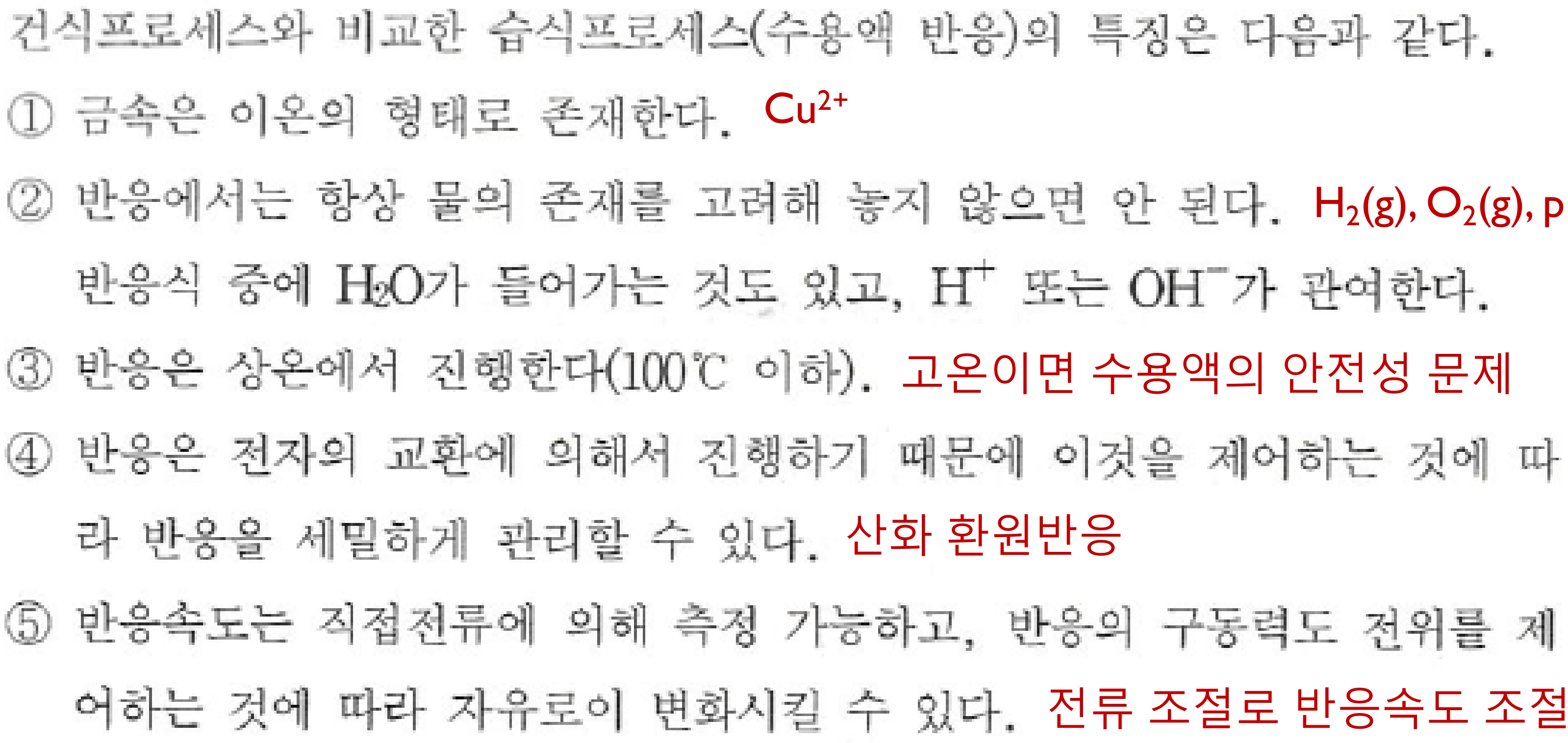
전기화학반응 프로세스의 특징



건식프로세스와 비교한 습식프로세스(수용액 반응)의 특징은 다음과 같다.

① 금속은 이온의 형태로 존재한다. Cu^{2+}

② 반응에서는 항상 물의 존재를 고려해 놓지 않으면 안 된다. $H_2(g)$, $O_2(g)$, pH 변화
반응식 중에 H_2O가 들어가는 것도 있고, H^+ 또는 OH^-가 관여한다.

③ 반응은 상온에서 진행한다(100℃ 이하). 고온이면 수용액의 안전성 문제

④ 반응은 전자의 교환에 의해서 진행하기 때문에 이것을 제어하는 것에 따라 반응을 세밀하게 관리할 수 있다. 산화 환원반응

⑤ 반응속도는 직접전류에 의해 측정 가능하고, 반응의 구동력도 전위를 제어하는 것에 따라 자유로이 변화시킬 수 있다. 전류 조절로 반응속도 조절 가능

Definition

① Electrodeposition (전기증착);

The deposition of a substance (mainly metals or oxides) on an electrode by the action of electricity (especially by electrolysis)

② Electrolysis (전기분해);

Lysis of a bond produced by the passage of an electric current

③ Electrolyte (전해질);

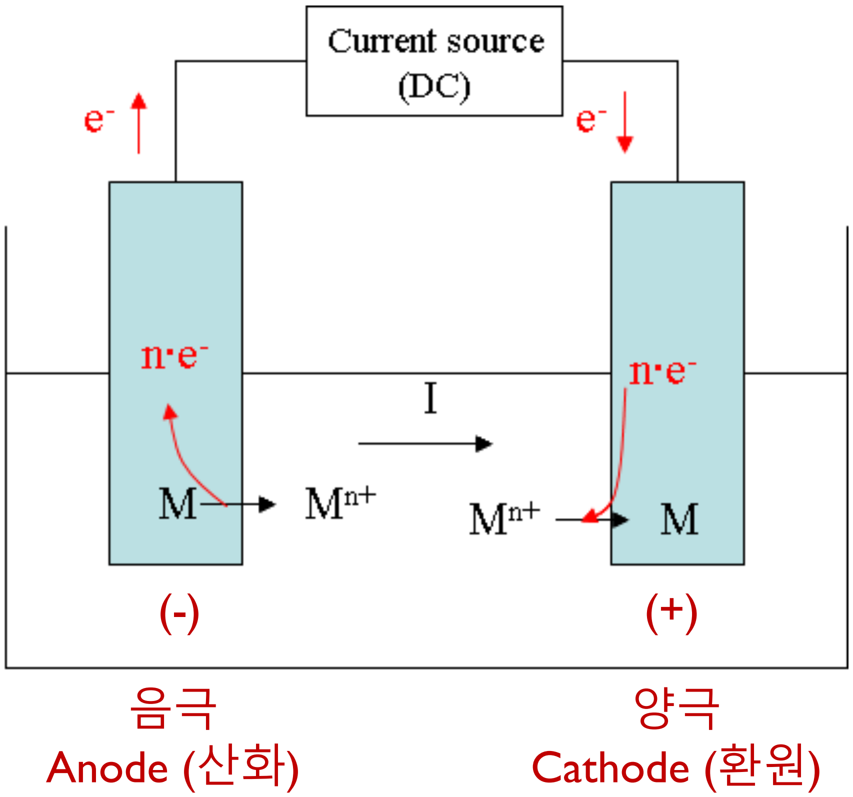
A solution that conducts electricity

④ Electrode (전극);

A conductor used to make electrical contact with some part of a circuit

Electrodeposition, Electroplating

Electrodeposition cell



- anode reaction; oxidation

$$M \rightarrow M^{n+} + n\,e^{-}$$

$$H_2O \rightarrow \frac{1}{2}O_2 + 2H^{+} + 2e^{-}$$

- cathode reaction; reduction

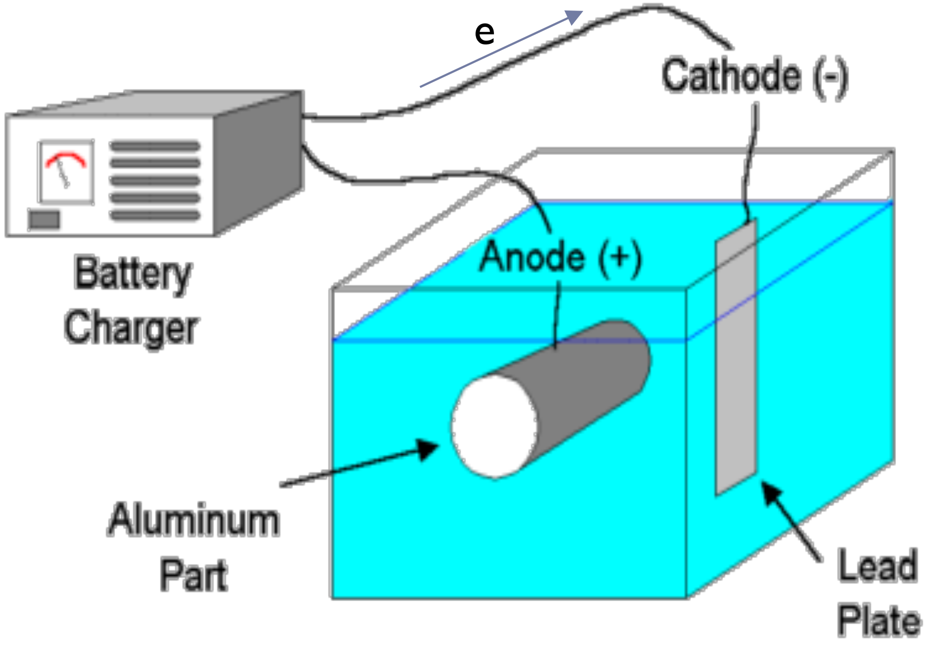
$$M^{n+} + n\,e^{-} \rightarrow M$$

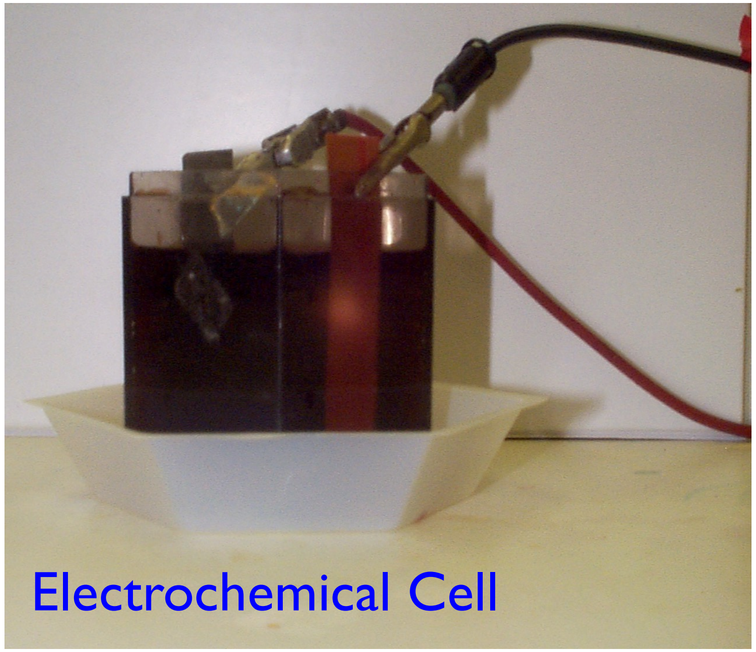
$$2H^{+} + 2e^{-} \rightarrow H_2$$

Equipments for Electrodeposition

Electrodeposition cell 의 구성

- Power supply (DC)
- Cathode (환원) → 도금을 당할 물체
- Anode (산화) → 금속이온 공급(도금용)
- Plating bath (금속이온)




Electrochemical Cell

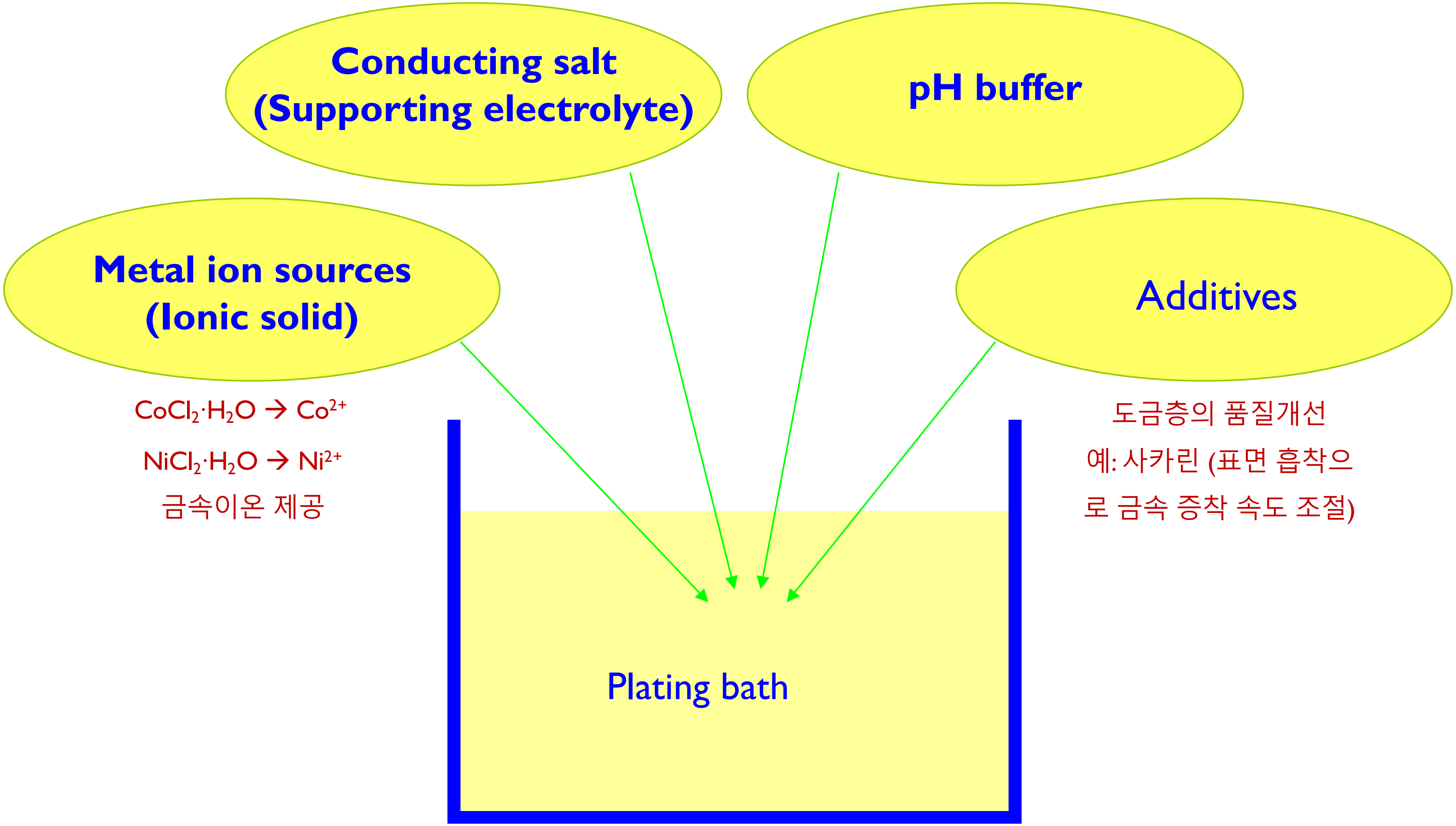
Electrodeposition Solution

용액 pH 안정화 : H_3BO_3 (붕산)

강산 → 수소발생 경쟁

강염기 → $M_x(OH)_y$ 생성

전도성 증가 (이온화가 쉬운): NaCl, Na_2SO_4



Conducting salt
(Supporting electrolyte)

pH buffer

Metal ion sources
(Ionic solid)

Additives

Plating bath

$CoCl_2 \cdot H_2O \rightarrow Co^{2+}$

$NiCl_2 \cdot H_2O \rightarrow Ni^{2+}$

금속이온 제공

도금층의 품질개선

예: 사카린 (표면 흡착으로 금속 증착 속도 조절)

Electroplating Bath

① Metal Ion Source

ex) CoNi thin film alloy를 도금하고자 할 때

- bath type 결정

  chloride bath, sulfer bath, sulfamate bath, Watts-type bath 등 중에서 어느 것?

  높은전도성 빠른 도금속도 / 환경친화 저렴한비용 / 균일한 도금층 생성 / 균일한 도금층 생성

- chloride bath로 결정했다고 가정,

  metal ion sources 인 chemicals 를 선택

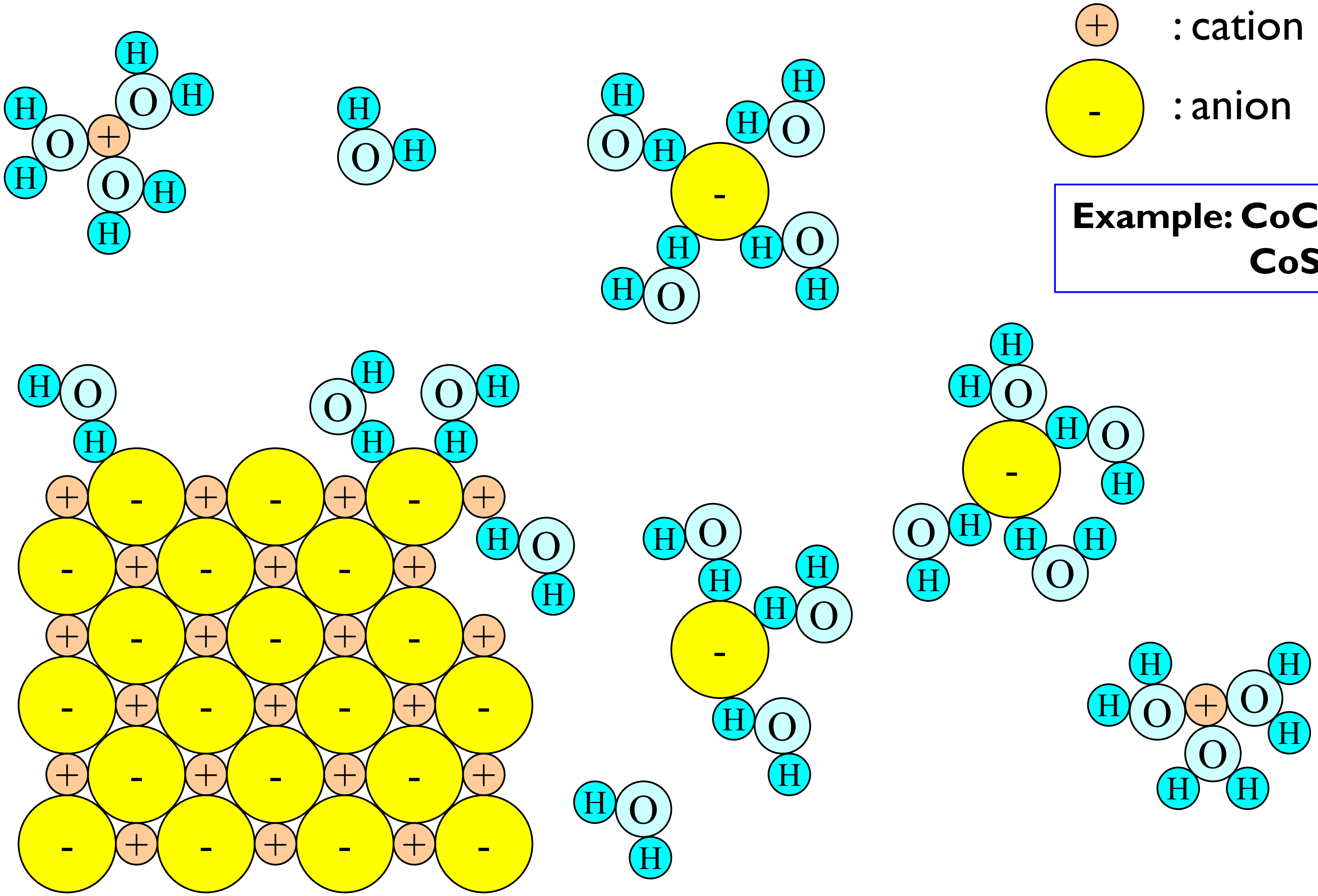
  $CoCl_2.6H_2O$ → Co source

  $NiCl_2.6H_2O$ → Ni source

- $CoCl_2$ and $NiCl_2$ → ionic solid; ionic bonding

  Ionic bonding; a primary bond arising from the electrostatic attraction between two appositely charged ions.

Ionic Solid in Water



+ : cation

- : anion

Example: $CoCl_2$, NaCl
$CoSO_4$, $NaSO_4$

Electroplating Bath

② Conducting salts (supporting electrolyte)

; 전류가 흐르도록 하기 위하여 넣어주는 화학약품

ex) chloride bath; NaCl

sulfate bath; Na_2SO_4

③ pH buffer

; a defined solution that resists change in pH when a small amount of an acid or base is added or when solution is diluted.

This is very useful for maintaining the pH for a reaction at an optimum value.

ex) H_3BO_3

④ Additives

; 전기도금에 의해 음극에 deposit 된 film 의 stress 나 surface 를 미려하게 하기 위하여 첨가하는 첨가제

ex) Saccharin

Electroplating Bath- examples

- Chloride bath

0.2 M	$CoCl_2$
0.206 M	$NiCl_2$
0.7M	$NaCl$
0.4 M	H_3BO_3
0.0048 M	Saccharin

- Sulfate bath,

0.2 M	$CoSO_4$
0.206 M	$NiSO_4$
0.7M	$NaSO_4$
0.4 M	H_3BO_3
0.0048 M	Saccharin

- Sulfamate bath,

0.2 M	$Co(NH_2SO_3)_2$
0.206 M	$Ni(NH_2SO_3)_2$
0.7M	$Na \cdot NH_2SO_3$
0.4 M	H_3BO_3
0.0048 M	Saccharin

Electroplating Bath- examples

- Ni (pure) electrodeposition

※ Calculation of each chemicals to make Ni plating bath

$0.2M\ NiCl_2.6H_2O$

0.7M NaCl

$0.4M\ H_3BO_3$

1g/L Saccharin (Sodium O-Benzoic Sulfimide) ; 205.16 g/mol

- case 1) Make total 1 liter solution

- case 2) Make total 300 mL solution

Molarity, M (몰농도)

※ Molarity, M (mole/l)

; a ration giving the number of moles of solute (용질) per 1 liter of solution (용액)

$$Molarity(M) = \frac{mole\ of\ solute}{\ell\ of\ solution}(mole/\ell)$$

ex) a solution containing 1 mole of KBr in 1L of solution → 1M(molar) solution

※ Concept of mole (mole)

6.02×10^{23} iron atoms ⇒ 1 mole iron atoms

- Avogadro's number; 6.02×10^{23}

- A mole is 6.02×10^{23} objects.

ex) 1 mole atoms = 6.02×10^{23} atoms

- conversion factors $\frac{1\ mole}{6.02 \times 10^{23}\ objects}$ 또는 $\frac{6.02 \times 10^{23}\ objects}{1\ mole}$

Mass of Mole (몰질량, g/mol)

The molar mass of an element (when the element is in atomic form) is a mass in grams that is numerically equal to the atomic mass of the element.

Atomic weight

- Mass of 1 carbon atom = 12.011 amu (atomic mass unit)

- Mass of 1 mole of carbon atom = 12.011 g/mol (molar mass)

ex) 6.02×10^{23} Cl atoms = 1 mole Cl atoms = 35.453 g/mol

ex) 44.0 g/mol = 1 mole CO_2

Atomic mass	Atomic weight
C^{12} = 12.0000 amu C^{13} = 13.0034 amu	C = 12.0110 amu (or g/mol)

Mass of Mole

※ Formula mass (or formular weight, 화학식 질량);

The sum of the atomic mass of the atoms present in one formula unit of the substance.

ex) $Na_2S_2O_3$

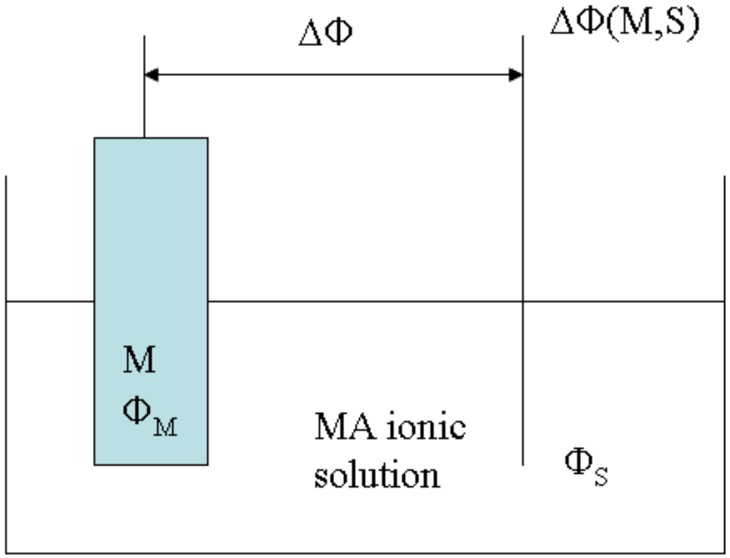
atomic weight of Na; 22.989768 g/mol, S; 32.066 g/mol, O; 15.9994 g/mol

formula mass of $Na_2S_2O_3$ =

(22.989768×2)+(32.066×2)+(15.9994×3) = 158.110 g/mol

Easy Nickel And Copper Electroplating Method
https://www.youtube.com/watch?v=Q8Xo43sfLgY

Electrode Potential (전극전위)



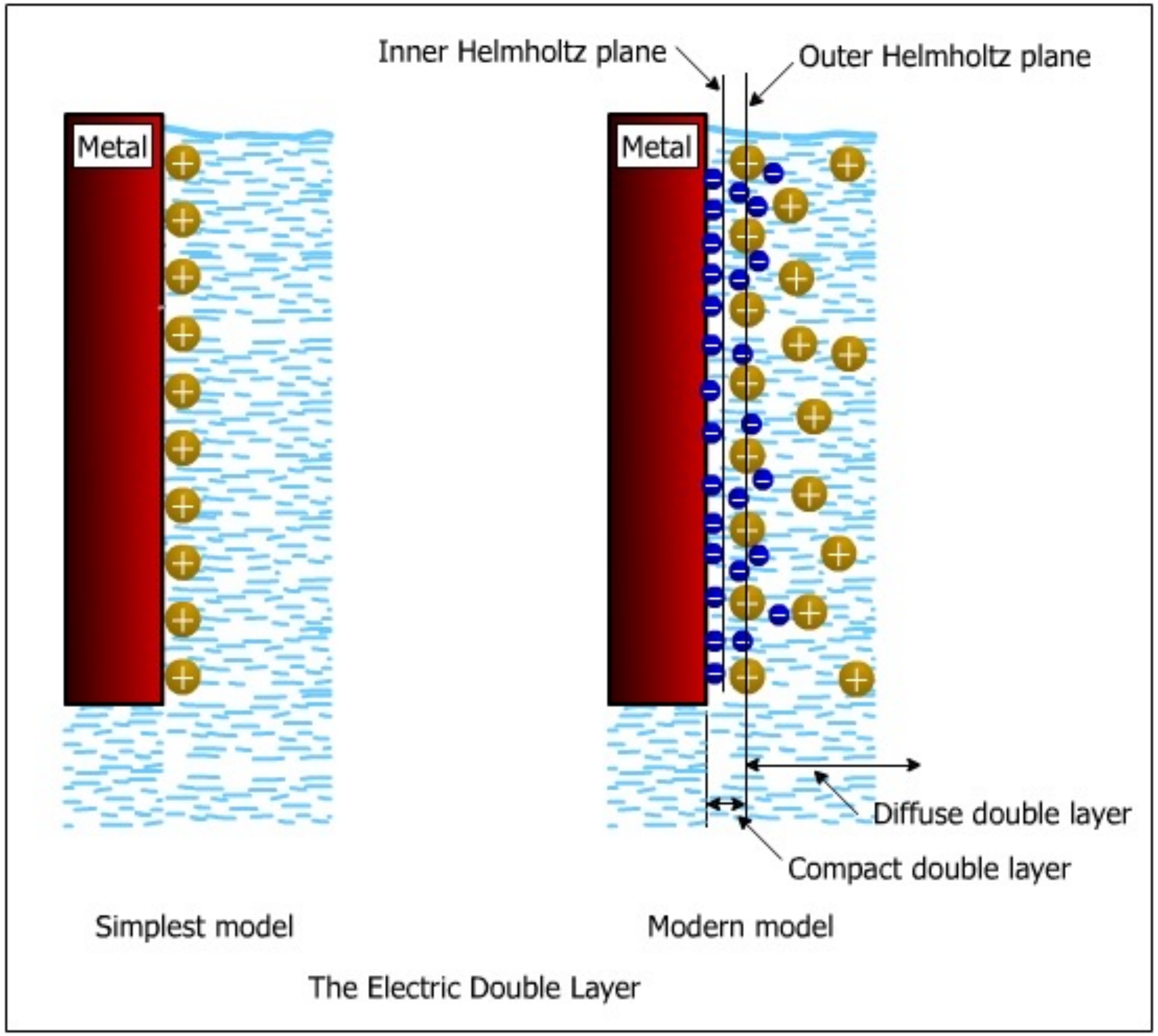
MA ; M^{Z+} and A^{Z-}
$M^{Z+} + z\,e \rightleftharpoons M$

where M; a metal
z; number of e^- involved in the reaction

- Reduction; Reaction from left to the right consumes electrons.
- Oxidation; Reaction from right to the left liberates electrons.

TheMAD

Helmholtz Double Layer



- When a metal dissolves continuously, it may become increasingly negatively charged because of passage of continuous positive ions in the solution. The excess negative charge on the metal surface balances the excess positive charge and the solution side of the interface and hence, a separation of charges exists.
- The electrons orient themselves opposite a layer of cations of equal and opposite charges on the solution side of the interface. The electric field which is created consists of two layers of charges; hence it has been given a name double layer. The separation of charges in the double layer can be compared to parallel plates in a capacitor as it was done by Helmholtz. The double layer is also called Helmholtz Double Layer.

http://faculty.kfupm.edu.sa/ME/hussaini/Corrosion%20Engineering/02.05.04.htm

Electrode Potential

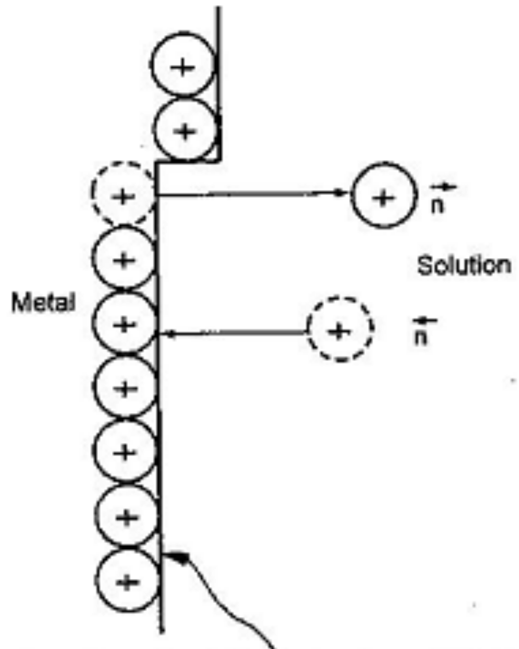


Figure 1 Formation of metal-solution interphase; equlibrium state: $\vec{n} = \overleftarrow{n}$.

$\vec{n}$; number of M^{Z+} ions which leave crystal lattice
$\overleftarrow{n}$; number of M^{Z+} ions which enter crystal lattice

at the dynamic equilibrium,

$$\vec{n} = \overleftarrow{n}$$

The inter-phase region is neutral at equilibrium.

$$q_M = -q_S$$

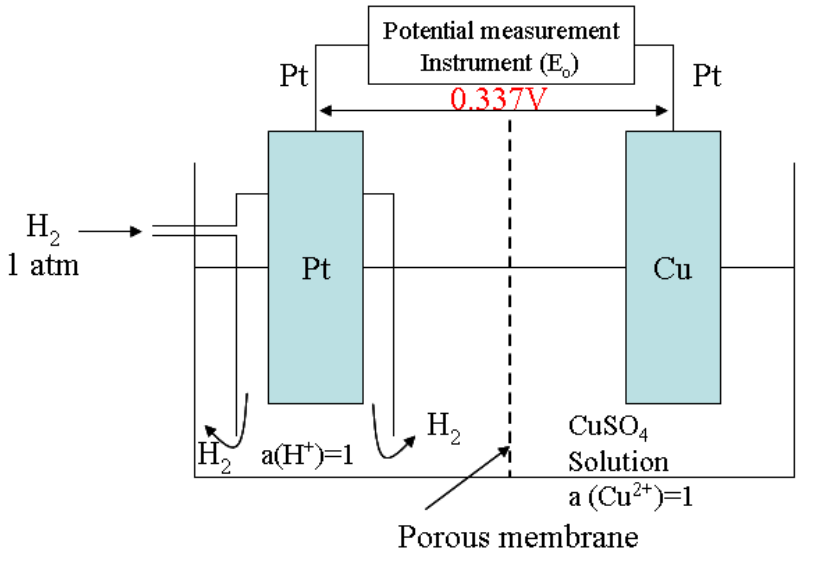
q_M^-; the charge on the metal per unit area
$q^+{}_S$; the charge per unit area on the solution side of the inter-phase

$\Delta\Phi(M,S)=\Phi_M - \Phi_S$

; the potential difference between the potentials of metal, Φ_M, and the solution, Φ_S, from the result of the charging of the inter-phase

Electrode Potential

In order to measure the potential difference of an inter-phase, one must connect it to another one and thus form an electrochemical cell.

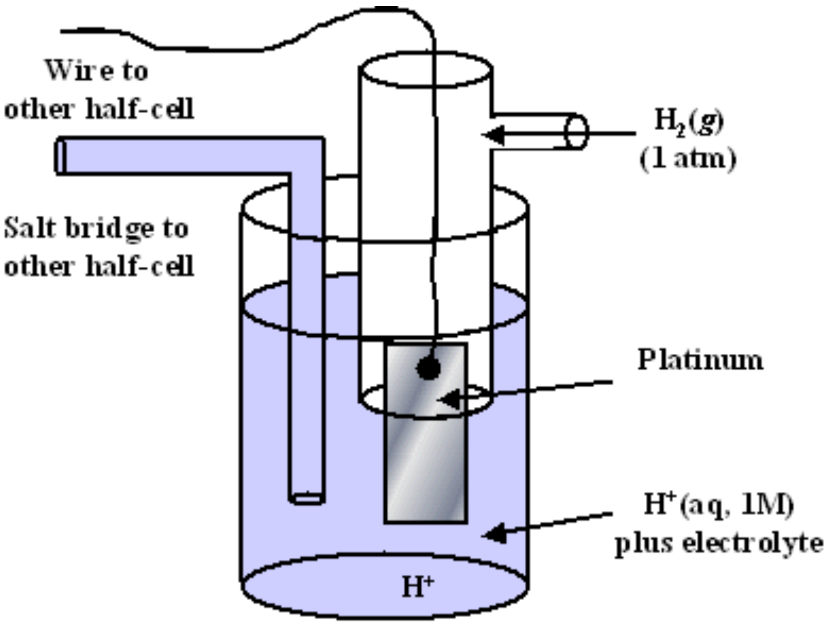


<Relative standard electrode potential E° of Cu/Cu⁺ electrode>

$$Pt, H_2\,(p=1)\,|\,H^+\,(a=1)\,||\,Cu^{2+}\,(a=1)\,|\,Cu\,|\,Pt$$

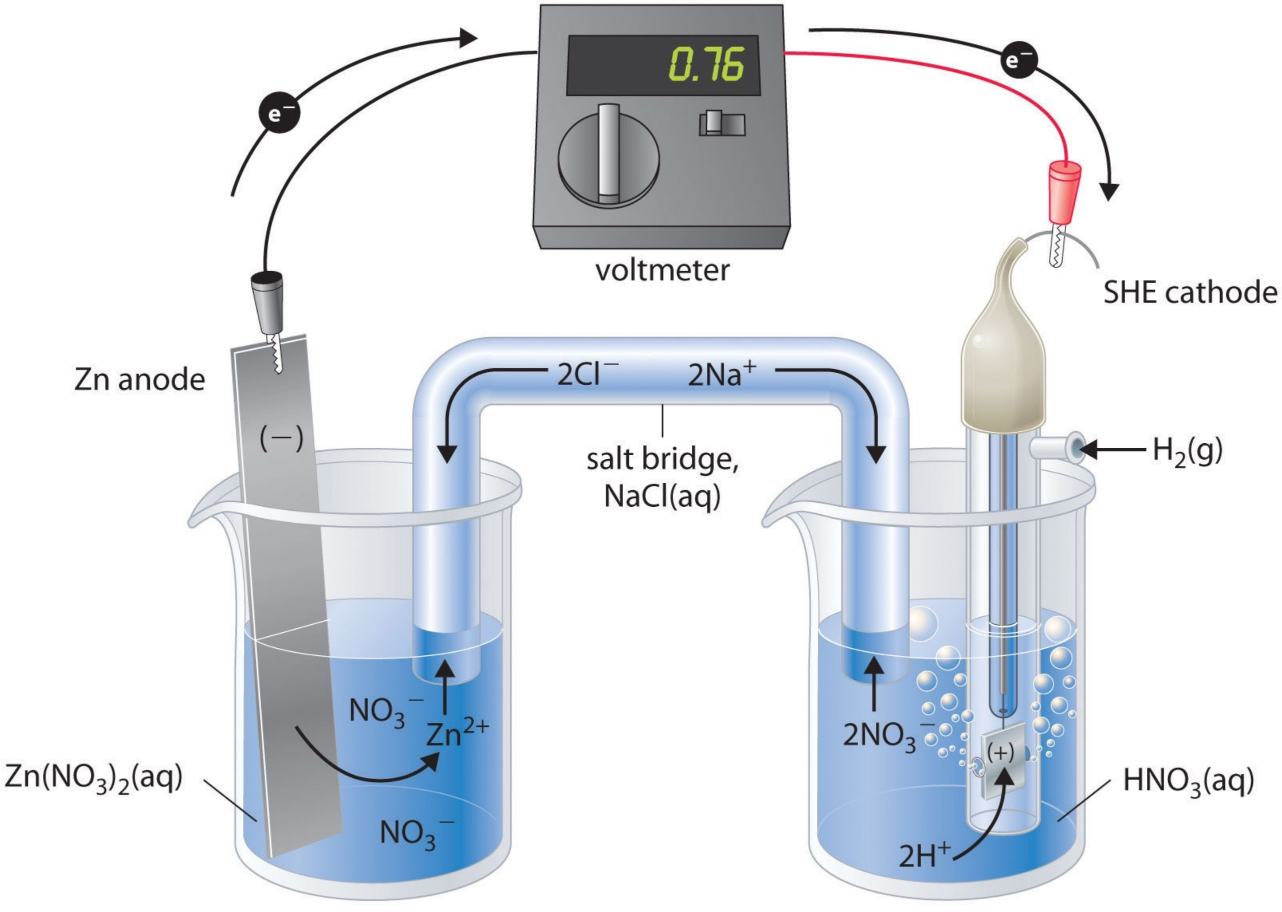
standard hydrogen electrode (SHE), a; activity, p; pressure of H_2

Hydrogen reference electrode



http://www.ips-jaissle.de/en/H2REFEL_En.html

Standard Electrode Potential



oxidation half-reaction:
$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$

reduction half-reaction:
$2H^+(aq) + 2e^- \rightarrow H_2(g)$

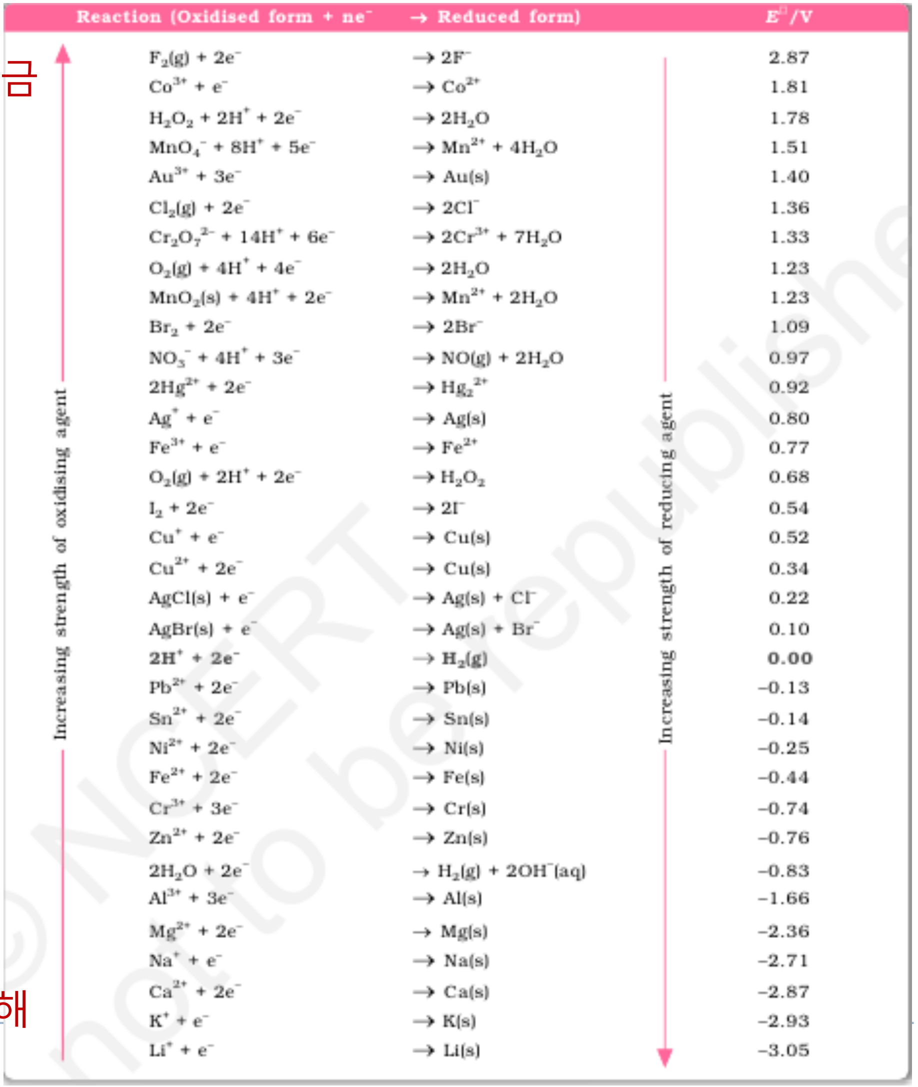
overall reaction: $Zn(s) + 2H^+(aq) \rightarrow Zn^{2+}(aq) + H_2(g)$

http://2012books.lardbucket.org/books/principles-of-general-chemistry-v1.0/s23-02-standard-potentials.html

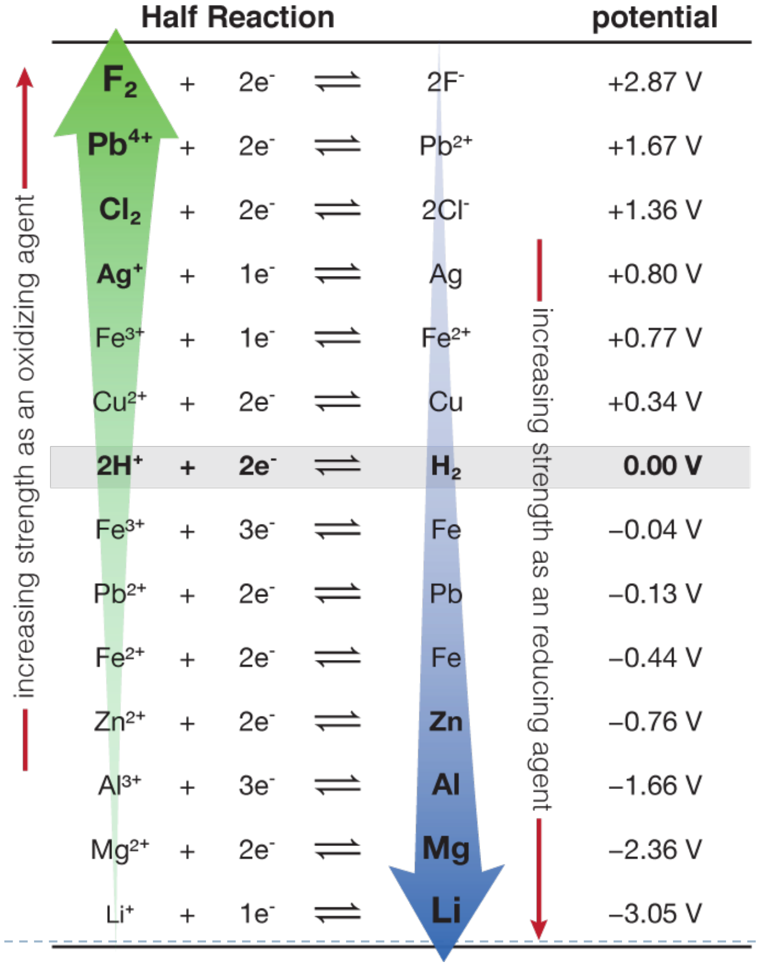
Standard Electrode Potential (표준전극전위)

the relative standard electrode potential of Cu, E^o; +0.337V

→ cell potential ; in volts (V), 1 V = 1 joule/coulomb (J/C)



Reaction (Oxidised form + ne⁻	→ Reduced form)	$E^\ominus$/V
$F_2(g) + 2e^-$	$\rightarrow 2F^-$	2.87
$Co^{3+} + e^-$	$\rightarrow Co^{2+}$	1.81
$H_2O_2 + 2H^+ + 2e^-$	$\rightarrow 2H_2O$	1.78
$MnO_4^- + 8H^+ + 5e^-$	$\rightarrow Mn^{2+} + 4H_2O$	1.51
$Au^{3+} + 3e^-$	$\rightarrow Au(s)$	1.40
$Cl_2(g) + 2e^-$	$\rightarrow 2Cl^-$	1.36
$Cr_2O_7^{2-} + 14H^+ + 6e^-$	$\rightarrow 2Cr^{3+} + 7H_2O$	1.33
$O_2(g) + 4H^+ + 4e^-$	$\rightarrow 2H_2O$	1.23
$MnO_2(s) + 4H^+ + 2e^-$	$\rightarrow Mn^{2+} + 2H_2O$	1.23
$Br_2 + 2e^-$	$\rightarrow 2Br^-$	1.09
$NO_3^- + 4H^+ + 3e^-$	$\rightarrow NO(g) + 2H_2O$	0.97
$2Hg^{2+} + 2e^-$	$\rightarrow Hg_2^{2+}$	0.92
$Ag^+ + e^-$	$\rightarrow Ag(s)$	0.80
$Fe^{3+} + e^-$	$\rightarrow Fe^{2+}$	0.77
$O_2(g) + 2H^+ + 2e^-$	$\rightarrow H_2O_2$	0.68
$I_2 + 2e^-$	$\rightarrow 2I^-$	0.54
$Cu^+ + e^-$	$\rightarrow Cu(s)$	0.52
$Cu^{2+} + 2e^-$	$\rightarrow Cu(s)$	0.34
$AgCl(s) + e^-$	$\rightarrow Ag(s) + Cl^-$	0.22
$AgBr(s) + e^-$	$\rightarrow Ag(s) + Br^-$	0.10
$2H^+ + 2e^-$	**$\rightarrow H_2(g)$**	**0.00**
$Pb^{2+} + 2e^-$	$\rightarrow Pb(s)$	–0.13
$Sn^{2+} + 2e^-$	$\rightarrow Sn(s)$	–0.14
$Ni^{2+} + 2e^-$	$\rightarrow Ni(s)$	–0.25
$Fe^{2+} + 2e^-$	$\rightarrow Fe(s)$	–0.44
$Cr^{3+} + 3e^-$	$\rightarrow Cr(s)$	–0.74
$Zn^{2+} + 2e^-$	$\rightarrow Zn(s)$	–0.76
$2H_2O + 2e^-$	$\rightarrow H_2(g) + 2OH^-(aq)$	–0.83
$Al^{3+} + 3e^-$	$\rightarrow Al(s)$	–1.66
$Mg^{2+} + 2e^-$	$\rightarrow Mg(s)$	–2.36
$Na^+ + e^-$	$\rightarrow Na(s)$	–2.71
$Ca^{2+} + 2e^-$	$\rightarrow Ca(s)$	–2.87
$K^+ + e^-$	$\rightarrow K(s)$	–2.93
$Li^+ + e^-$	$\rightarrow Li(s)$	–3.05



Half Reaction					potential
F_2	+	$2e^-$	⇌	$2F^-$	+2.87 V
Pb^{4+}	+	$2e^-$	⇌	Pb^{2+}	+1.67 V
Cl_2	+	$2e^-$	⇌	$2Cl^-$	+1.36 V
Ag^+	+	$1e^-$	⇌	Ag	+0.80 V
Fe^{3+}	+	$1e^-$	⇌	Fe^{2+}	+0.77 V
Cu^{2+}	+	$2e^-$	⇌	Cu	+0.34 V
$2H^+$	**+**	**$2e^-$**	⇌	**H_2**	**0.00 V**
Fe^{3+}	+	$3e^-$	⇌	Fe	–0.04 V
Pb^{2+}	+	$2e^-$	⇌	Pb	–0.13 V
Fe^{2+}	+	$2e^-$	⇌	Fe	–0.44 V
Zn^{2+}	+	$2e^-$	⇌	**Zn**	–0.76 V
Al^{3+}	+	$3e^-$	⇌	**Al**	–1.66 V
Mg^{2+}	+	$2e^-$	⇌	**Mg**	–2.36 V
Li^+	+	$1e^-$	⇌	**Li**	–3.05 V

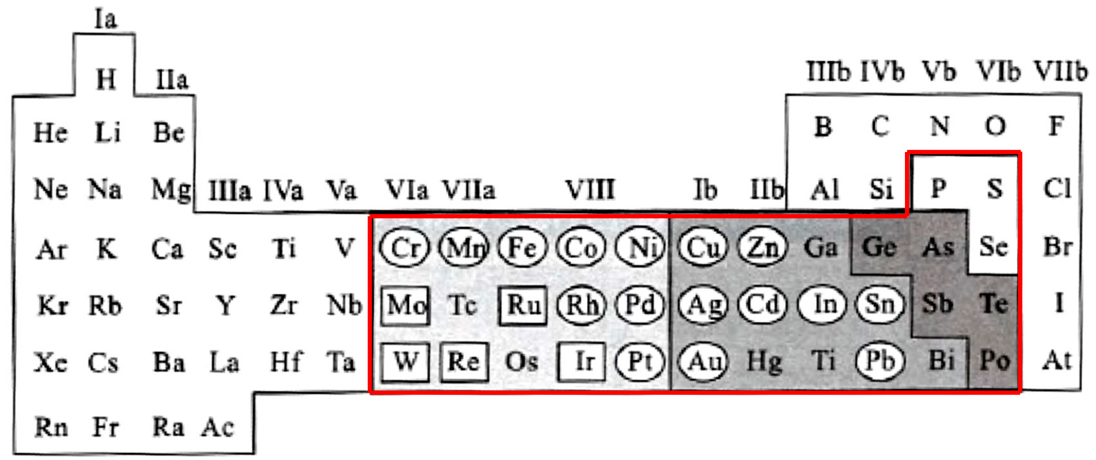
희생양극 (갈바닉 보호)

Standard Electrode Potential

- Non-plating metals from aqueous solutions

; more negative reduction potential of the metal ions than that of solvent and supporting electrolyte

표 3・4 수용액에서 전극 표면에 석출될 수 있는 금속의 주기율표상의 위치



▨ metals which can deposit on the solid cathode alone or as an alloy such as Mo, W–iron-group metals, P–Ni, S–Ni or Bi–Se.

○ metals which are important in the practical use.

☐ metals whose application has been recently developed.

Nernst equation

; concentration dependence of equilibrium cell voltage

$$aA + bB + \ \dots \ = mM + nN + \ \dots \qquad (1)$$

free energy change (ΔG) as a function of cell voltage (E)

$$\Delta G = -zFE \qquad (2)$$

전위차 (E) 가 크면 ΔG << 0 → 반응이 잘 일어남

where, *z* ; number of electrons involved in the reaction
F ; Faraday number (96,487 C/mol)　　I mole 의 전자가 가지는 총 전하량
E ; the cell voltage

식 (2)의 유도,
electric work, *W*

$$\begin{aligned} W &= qV \\ \Delta G &= -W \\ &= -qV \\ &= -zFE \end{aligned}$$

$V: the\ voltage\ (E)$
$W: the\ work\ done\ (\Delta G)$
$q: total\ charge\ (C, zF)$

Nernst equation

Free energy change as a concentration (activity) of the reaction

$$\Delta G = \Delta G^o + RT\ln Q \qquad (3)$$

$$\text{where, } Q = \frac{a_M^m \cdot a_N^n \cdot \cdot \cdot}{a_A^a \cdot a_B^b \cdot \cdot \cdot} = \frac{\Pi[\,products\,]}{\Pi[\,reactants\,]} \qquad (4)$$

where, R; the gas constant (8.314 J/mol•K), T; the absolute temperature, *Π*; the product of the concentrations (activities, a) raised to the power of their stoichiometric number, Q; reaction quotient (반응지수, 반응물과 생성물 농도 비율)

For standard states, when activities of the reactants and products equal 1
From eq. (2) and (3)

$$\Delta G^o = -zFE^o \qquad (5)$$

Where, ΔG^o is the standard free-energy change (모든 농도가 1M)
E^o is the cell voltage for standard states of reactants and products

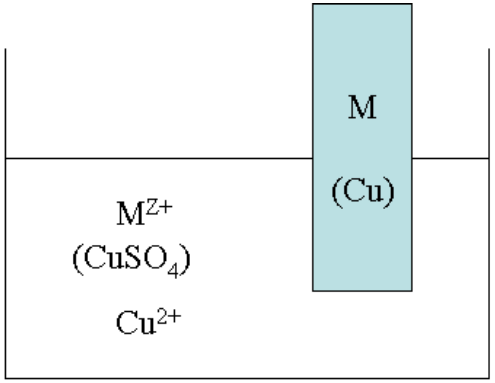
put eq. (2) and (5) into eq. (3)

$$-zFE = -zFE^o + RT\ln Q \qquad (6)$$

$$E = E^o - \frac{RT}{zF}\ln Q \quad \text{or} \quad E = E^o + \frac{RT}{zF}\ln\frac{1}{Q} \qquad (7)$$

$$E = E^o + \frac{RT}{zF}\ln\frac{\Pi[\,reactants\,]}{\Pi[\,products\,]} \qquad (8)$$

⇒ dependence of the equilibrium cell voltage on the concentration ex) Metal/Metal-ion (M/M^{z+}) electrode potentials are the results of an exchange of metal ions between metal and electrolyte



The electrode potential of this electrode depends on the concentration (more exactly, the activity) of the metal ions M^{z+} in solution.

The Nernst equation for the concentration dependence of metal/metal-ion potential

$$M^{z+} + ze \leftrightarrow M$$

reduction reaction consumes electrons

oxidation reaction liberates electrons

$$Pt \mid H_2\,(1\,atm) \mid H^+\,(a=1) \parallel M^{z+} \mid M$$

From eq. (8)

$$E = E^{o} + \frac{RT}{zF}\ln\frac{[M^{z+}][e]^{z}}{[M]}$$

where, [ ] is the activity of the species inside the those brackets.

Since the activities of metal(M) and electrons(e) in the metal lattice both equal 1 by convention.

$$E = E^{o} + \frac{RT}{zF}\ln[M^{z+}]$$

convert the natural logarithm into decimal logarithm

$$E = E^{o} + \frac{RT}{zF}2.303\log[M^{z+}]$$

$$\frac{RT}{F} = 0.0257\ V \text{ at } 298\text{K } (25\,℃)$$

$$\frac{8.31J/mol\,K \times 298K}{96487\ C/mol} = 0.0257\ J/C = 0.0257\ V$$

$$\therefore\ E = E^{o} + \frac{0.0592}{z}\log[M^{z+}] \qquad (9)$$

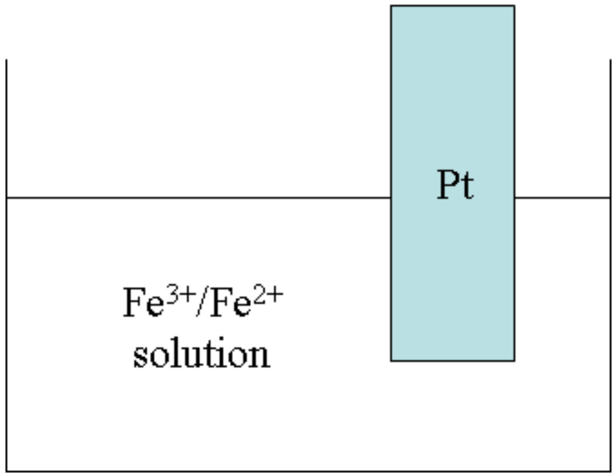
Activity = 1

- 순수한 고체 금속
- 순수한 액체 물
- 순수한 고체 화합물
- 전자

In case of standard state (1atm, 1M)

- 기체
- 용액
- 고체/액체

ex) RedOx (RED/OX) electrode potentials are the result of an exchange of electrons between metal and electrolyte.



The electrolyte in the RedOx system contain two substances;

- electron donors (electron-donating species)
- electron acceptors (electron-accepting species)

ex) Fe^{3+}/Fe^{2+} RedOx system;

RedOx reaction

$$Fe^{3+} + e \leftrightarrow Fe^{2+}$$

Pt ; the electrode

Fe^{3+} ; the oxidized form

Fe^{2+} ; the reduced form

the general RedOx electrode reaction;

$$Ox + z\,e \leftrightarrow Red$$

where, Ox; the oxidized ions

Red; the reduced ions

ex) Complex RedOx reaction involving H^+

$$MnO_4^- + 5e + 8H^+ \leftrightarrow Mn^{2+} + 4H_2O$$

The Nernst equation for concentration dependence of RedOx potential

From eq. (8)

$$E = E^o + \frac{RT}{zF}\ln\frac{[Ox]}{[Red]}$$

If the activities of the reactants(Ox) and the product(Red) are equal to 1,

[Ox]=1, [Red]=1

$E = E^o$

E^o ; the standard electrode potential of the RedOx electrode

Kinetics and mechanism of electrodeposition

① Faraday's law for electrolysis

Faraday's law ; the amount of electrochemical reaction that occurs at an electrode is proportional to the quantity of electric charge Q passed through an electrochemical cell.

$$W = Z \cdot Q \qquad (10)$$

where, W ; the weight of a product of electrolysis (g)
Q ; the quantity of electric charge (C)
Z ; the electrochemical equivalent (g/C) 1C 으로 생성되는 물질의 양

$$Q = I \cdot t \qquad (11)$$

where, I ; the current (in amperes, A)
t ; the elapsed time (in seconds, s)

$$\therefore W = Z \cdot I \cdot t \qquad (12)$$

* Faraday constant, F ; 96,487 C/mol

Coulomb is the quantity of electricity transported by the flow of one ampere for one second

$$1C = 1\ A \cdot sec$$

$$F = N_A \cdot e = (6.0225 \times 10^{23})(1.6021 \times 10^{-19}) = 96,487\ C/mol$$

$$where,\ N_A ; Avogadro's\ number,\ 6.0225 \times 10^{23}\ molecules/mol$$

$$e ; the\ charge\ of\ a\ single\ electron,\ 1.6021 \times 10^{-19}\ C$$

* One equivalent, Weq; (1그램 당량 – 1몰의 전자와 반응하는 물질의 질량)

Fraction of a molar (atomic) unit of reaction that corresponds to the transfer of one electron

$$W_{eq} = \frac{A_{wt}}{n} \qquad (13)$$

where, A_{wt} ; the atomic weight of metal deposited on the cathode

n ; number of electron involved in the electrodeposition reaction

ex) $\mathrm{Ag} \leftrightarrow \mathrm{Ag}^{+}$

$$\text{for Ag,}\ W_{eq} = \frac{gram\ atomic\ weight\ of\ Ag}{1} = \frac{107.88}{1} = 107.88$$

ex) $\mathrm{Cu} \leftrightarrow \mathrm{Cu}^{2+}$

$$\text{for Cu,}\ W_{eq} = \frac{gram\ atomic\ weight\ of\ Cu}{\mathbf{2}} = \frac{63.546}{2}$$

If, $Q = 1$ Coulomb or $Q = 1\ \mathrm{A \cdot sec}$

$$W_{Q=1} = Z \qquad (14)$$

thus, the electrochemical equivalent of a metal M, Z(M), is the weight in grams produced, or consumed, by one coulomb (one ampere second)

$$W = W_{Q=1} \bullet Q \qquad (15)$$

Since 96,487 coulombs are required for the electrodeposition of an equivalent of a metal, Weq,

$$W_{eq} = 96,487 \bullet Z$$

Weq = 1몰의 전자와 반응하는 물질의 양 g/mol
Z = 1C의 전기량으로 생성되는 물질의 양 g/C
F = 1몰의 전자의 전기량 C/mol

and

$$Z = W_{Q=1} = \frac{W_{eq}}{96,487} = \frac{W_{eq}}{F} \qquad (16)$$

From eq. (13) and eq. (16)

$$Z = \frac{A_{wt}/n}{F} = \frac{A_{wt}}{nF} \qquad (17)$$

From eq. (10) and eq. (17)

$$W = Z \bullet Q = \frac{A_{wt}}{nF} Q = \frac{A_{wt} \bullet I \bullet t}{nF} \qquad (18)$$

Current efficiency

From Faraday's law, the overall amount of chemical change produced by any given quantity of electricity can be exactly accounted for.

the current efficiency, CE

$$CE = \frac{M_a}{M_t} \times 100$$

where M_a ; the actual amount of metal deposited (or dissolved)

M_t ; the theoretically calculated amount of metal from Faraday's law

If all the applied current had been used for depositing the metal to the cathode, it is called the cathode efficiency. (CE = 100%)

- The factors effected on the cathode efficiency
    - electrolyte or bath
    - chemical component concentrations
    - pH
    - Agitation (교반)
    - current density

Current density and distribution

Not uniform thickness from one edge of the cathode to the other from electrodeposition process

⇒ the possible presence of discontinuities in forms of pores, cracks and other irregularities

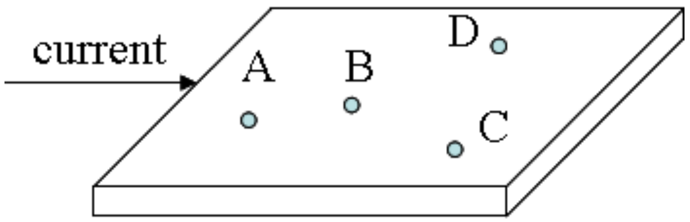
- Definition of current density

$$J = \frac{di}{ds}$$

where, J ; the magnitude of the current density

di ; the element of current impinging on ds

ds ; the element of cathode surface area



The current density over a cathode will vary from point to point.

Current tends to concentrate at edges and protruding points. (튀어나온)

Current tends to be low in recesses, vias, and cavities. (들어간)

- Electric field strength ; $E = \frac{V}{L}$

Current tends to flow more readily to points nearer to the opposite electrode than to more distant points.
The thickness of deposit will tend to vary over the surface of the cathode and be thicker at edges and points (bumps)

* The factors effected on the uniformity of deposited metal
    - the shape and dimensions of the object
    - the geometry of the plating cell
    - the conductivity of the bath
    - the shape of polarization curves,
    - CE-current density (or similar) curves
    - the effect of agitation