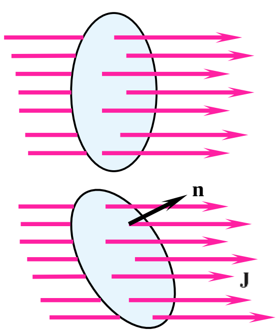
Chap. 5. 도체 및 유전체

- 전압 (chap 4) , 도체 , 전류 , 저항 , 회로
- E(2장) → D(3장) → V(4장) → I,R(5장) → C(6장)
- Material :
  - 도체 – 도전율 (σ) , 저항 　 R , Ohm's Law , Circuit (5장)
  - 유전체 – 유전율 (ε) , 정전용량 　 C , (6장)
  - 반도체 – Mobility (μ) 　 L 　 * Inductance
  - 초전도체

5.1 전류 , 전류밀도

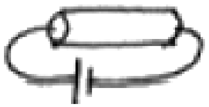
- 전류 : 전하의 이동. $\boxed{I = \dfrac{dQ}{dt}}$
  - 1초에 1 Coulomb 의 전하의 이동 = 1 Ampere
  - $1[C] = \dfrac{1}{1.6\times10^{-19}} \cong 10^{19}$ 개의 electron

- 전류와 전류밀도 : $\boxed{I = \int_S \mathbf{J}\cdot d\mathbf{S}}$
  - I : [A]
  - $\mathbf{J}$: $[A/m^2]$



• <u>전류의 종류</u>

① 전도전류 (Conduction Cur.) :



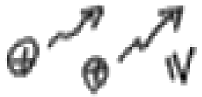
$$\boxed{\mathbf{J} = \sigma \mathbf{E}}$$

$$I = \frac{1}{R}V = GV$$

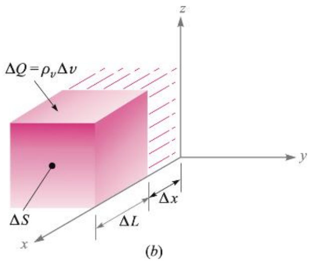
• R의 정의와 G

• σ : Conductivity

② 대류전류 (Convection Cur.) :



$$\boxed{\mathbf{J}_V = \rho_V \mathbf{V}}$$



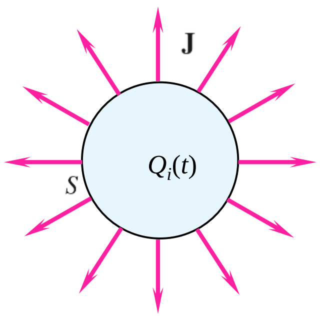
③ 변위전류 (Displacement Cur.) :

$$\boxed{\mathbf{J}_d = \frac{\partial \mathbf{D}}{\partial t}}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \qquad \mathbf{J}_d = \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

E, **D**, **J** ?

5.2 전류의 연속성



$$I = \oint_S \mathbf{J} \cdot d\mathbf{S} = -\frac{dQ_i}{dt} = -\frac{d}{dt}\int_{\text{vol}} \rho_v \, dv$$

$$\int_{\text{vol}} (\nabla \cdot \mathbf{J})\, dv = -\frac{d}{dt}\int_{\text{vol}} \rho_v \, dv$$

$\oint_S \mathbf{J} \cdot d\mathbf{S} = \int_{\text{vol}} (\nabla \cdot \mathbf{J})\, dv$: divergence theorem

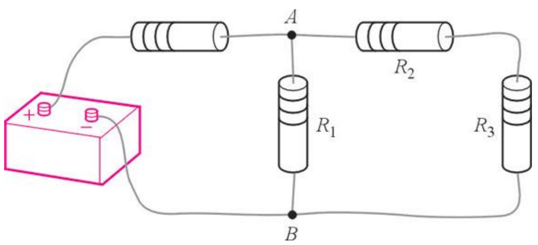
$$\int_{\text{vol}} (\nabla \cdot \mathbf{J})\, dv = \int_{\text{vol}} -\frac{\partial \rho_v}{\partial t}\, dv$$

$\boxed{(\nabla \cdot \mathbf{J}) = -\frac{\partial \rho_v}{\partial t}}$: *Current Continuity Equation*

- $I = \underbrace{\oint_S \mathbf{J} \cdot d\mathbf{S}}_{1} = \underbrace{-\frac{dQ}{dt}}_{2}$

$$\begin{cases} 1 = \int_v (\nabla \cdot \mathbf{J}) dv & (\because \text{ divergence theorem }) \\ 2 = -\frac{d}{dt}\int_v \rho_v dv \end{cases}$$

$$\therefore \int_v (\nabla \cdot \mathbf{J}) dv = \int_v \left(-\frac{\partial \rho}{\partial t}\right) dv$$



$\boxed{\therefore \nabla \cdot \mathbf{J} = -\frac{\partial \rho_v}{\partial t}}$: 전류의 연속식

$J \rightarrow$  $\rightarrow J'$ $\qquad \|\mathbf{J} - \mathbf{J}'\| = ?$

5.3 금속도체

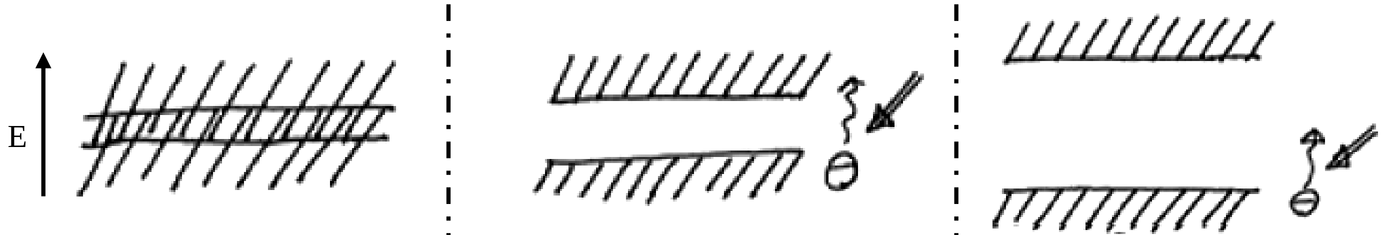
(도체 : 5.3절 , 반도체 : 5.6절 , 유전체 : 5.7절)

- 원자 = 전자 + 원자핵
- 양자역학 : quantized level :

- Energy band :

Empty conduction band	→ conduction band (전도대)
Energy gap	→ forbidden band (금지대)
Filled valence band	→ valence band (가전자대)

- Matter & Energy band :



v,b 전자들이
자유롭게 이동

(도체)

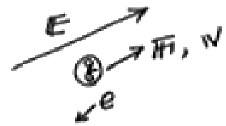
E. gap 작음
열, 빛, 전계 등으로 이동

(반도체)

E. gap 큼.

(절연체)

• 도전율 (Conductivity σ)



$$\begin{bmatrix} \text{힘} & \mathbf{F} = -e\mathbf{E} & : \text{Coulomb Force} \\ \text{속도} & \mathbf{V}_d = -\mu_0 \mathbf{E} & : \text{Drift Velocity} \end{bmatrix}$$

✓ μ_e : 전자이동도 (Mobility)

$[m^2/V \cdot S \doteq \frac{V}{E}]$ $\begin{bmatrix} \text{Al : 0.0012} \\ \text{Cu : 0.0032} \\ \text{Ag : 0.0056} \end{bmatrix}$

• 금속 내에서의 전류 $\mathbf{J} = \rho_e \cdot \mathbf{V} = \rho_e \cdot (-\mu_e \mathbf{E}) = -\rho_e \mu_e \mathbf{E} \equiv \sigma \mathbf{E}$ $\begin{bmatrix} \rho_e & : \text{자유전하의 전하밀도} \\ \mu_e & : \text{자유전하의 Mobility} \end{bmatrix}$

$\boxed{\therefore \mathbf{J} = \sigma\, \mathbf{E}}$ σ : Conductivity. 도전율

$$\begin{bmatrix} \sigma = \mathbf{J}/\mathbf{E} \quad \text{전계에 의한 전류비 , 물질고유상수} \\ \dfrac{\mathbf{J}}{\mathbf{E}} \quad \left[\dfrac{A/m^2}{V/m^2} = \dfrac{A/V}{m} \equiv \dfrac{\mho}{m}\right] \end{bmatrix}$$

$\boxed{\sigma = -\rho_e \mu_e}$

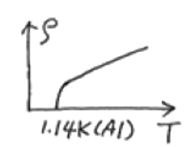
$\boxed{\sigma = -\rho_e \mu_e + \rho_h \mu_h}$

✓ $$\begin{bmatrix} \sigma \ : \text{conductivity ,} & G = \dfrac{I}{V} \ : \underline{\text{conductance}} & [\dfrac{A}{V}] \equiv mho \quad \mho \\ \rho(=\dfrac{1}{\sigma}) \ : \text{resistivity ,} & R = \dfrac{V}{I} \ : \underline{\text{resistance}} & [\dfrac{V}{A}] \equiv ohm \quad \Omega \end{bmatrix}$$

✓ σ : 물질고유상수 $\begin{bmatrix} Al = 3.8 \times 10^7, \ Cu = 5.8 \times 10^7, \ Ag = 6.17 \times 10^7, \ Au = 4.1 \times 10^7 \\ Fe = 1.03 \times 10^7, \ Si = 1.2 \times 10^3, \ \text{바닷물} = 5 , \ \text{다이아몬드} = 2 \times 10^{-13} \\ \text{수정} = 10^{-17} \quad \text{* Ring ?} \end{bmatrix}$

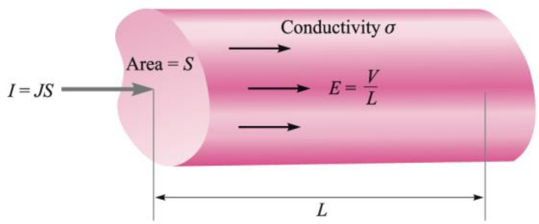
✓ ρ 의 온도의존성

$\begin{bmatrix} \sigma = -\rho_e \mu_e : \ \text{T} \uparrow , \text{격자운동} : \uparrow \ \ \mu_e \downarrow : \ \sigma \downarrow : \ \rho \uparrow \\ \text{온도 1K 상승시 } \rho \text{ 는 0.4\% 증가} \end{bmatrix}$



Super Conductivity

➢ 도체의 저항 R :



$$I = \int_S \mathbf{J} \cdot d\mathbf{S} \cong J \cdot S$$

$$V_{ab} = -\int_b^a \mathbf{E} \cdot d\mathbf{L} \cong -\mathbf{E} \cdot \mathbf{L} \qquad E = \frac{V}{L}$$

$$\therefore J\left(=\frac{I}{S}\right) = \sigma E = \sigma \frac{V}{L}$$

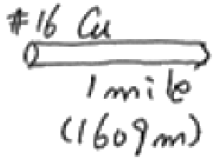
$$V = \frac{L}{\sigma S} I \equiv R \cdot I$$: Ohm's Law

$$\boxed{\therefore R = \frac{L}{\sigma S}}$$

$$R = \frac{V_{ab}}{I} = \frac{-\int_a^b \mathbf{E} \cdot d\mathbf{L}}{\int_S \mathbf{J} \cdot d\mathbf{S}} = \boxed{\frac{-\int_a^b \mathbf{E} \cdot d\mathbf{L}}{\int_S \sigma \mathbf{E} \cdot d\mathbf{S}}}$$

(Ex)

(Ex)　#16 동선, 1 mile 의 저항은 ?



: 직　경　$1.3mm = 1.3\times10^{-3}m$

단면적　$S = \pi(\frac{D}{2})^2 = 1.3\times10^{-6}m^2$

구　리　$\sigma = 5.8\times10^{7}$

$$\rightarrow R = \frac{L}{\sigma S} = \frac{1609}{5.8\times10^{7}\times1.3\times10^{-6}}$$

$$= 21.2[\Omega]$$

✓ 여기에 DC 10 [A]의 전류가 흐를 경우 내부에서는 ?

$$J = \frac{I}{S} = \frac{10}{1.3\times10^{-6}} = 7.65\times10^{6}[A/m^2] = 7.65[A/mm^2]$$ Safe ?

$$V = IR = 10\times21.2 = 212[V]$$ For 10[A]

$$E = \frac{V}{L} = \frac{212}{1609} = 0.312[V/m]$$

$$v_d = \mu_e E = 0.422\times10^{-3}[m/s]$$

$$\rho_e = -\frac{J}{v_d} = -1.81\times10^{10}[C/m^3]$$

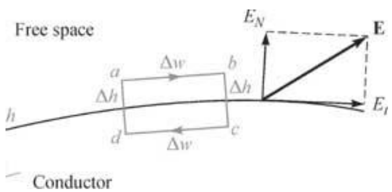
5.4 도체의 성질 및 경계조건

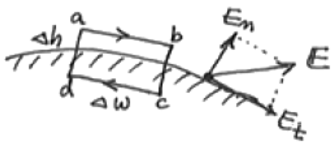
- 도체 내부의 전하 : Coulomb Force 로 표면으로 이동

(1) 도체 내부 : ① 전하는 도체의 표면에만 존재한다. : $\rho_m = 0$

② 도체 내부의 전계의 세기는 zero : $\mathbf{E}_m = \mathbf{0}$

(2) 도체 표면 ① E = ? :





Δh approaches zero

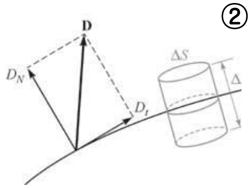
$$\oint \mathbf{E}\cdot d\mathbf{L} = 0 \qquad \int_a^b + \cancel{\int_b^c}_{\,0} + \int_c^d + \cancel{\int_d^a}_{\,0} = \mathbf{O}$$

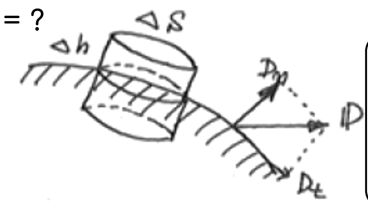
$$E_t \cdot \Delta W + 0(\because \text{도체내부}) = 0$$

$\boxed{E_t = \mathbf{O}}$ $\quad \mathbf{E}\times\mathbf{n}\big|_s = 0$ ✓ Tangential E is zero

$\boxed{\therefore V = const}$

② D = ?





$$\oint_S \mathbf{D}\cdot d\mathbf{S} = Q \qquad \int_{top} + \int_{bottom} + \cancel{\int_{side}}_{\,0} = \int_{\rho_S} dS$$

$$D_n \cdot \cancel{\Delta S} + 0(\because \text{도체내부}) = \rho_S \cancel{\Delta S}$$

$\boxed{\therefore D_N = \rho_S}$ $\quad \mathbf{D}\cdot\mathbf{n}\big|_s = \rho_S$ ✓ Normal D = surface charge density

➢ Sum : 도체내부 : $\rho = 0, \quad \mathbf{E} = \mathbf{0}$

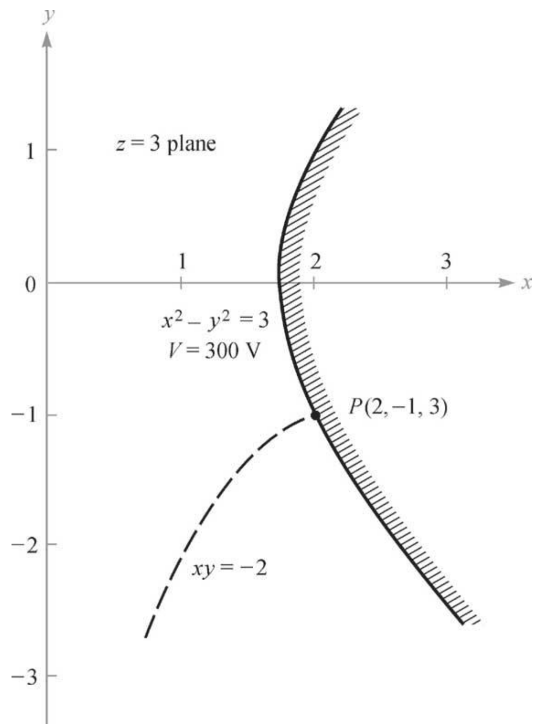
도체표면 : $E_t = 0 \rightarrow V = const$

$D_N = \varepsilon_0 E_N = \rho_S$, 전계는 모두 법선성분

* 도체표면에서

$$\begin{cases} D_t = E_t = 0 \\ D_N = \varepsilon_0 E_N = \rho_S \\ V = C \end{cases}$$

(Ex) $V=100(x^2-y^2)$, P (2 , -1 , 3) 경계면에서 V, $\mathbf{E}$, $\mathbf{D}$, ρ_S $=?$



- V_p = 300 [V]
- 도체에서 등전위이므로 도체형상식 , $300=100(x^2-y^2)$

  $\rightarrow x^2-y^2=3$, 포물선 모양 형상

- $\begin{cases} \mathbf{E}=-\nabla V=-100\cdot\nabla(x^2-y^2)-200x\hat{a}_x+200y\hat{a}_y \\ \mathbf{E}_P=-400\hat{a}_x-200\hat{a}_y \quad [V/m] \end{cases}$
- $\mathbf{D}_P=\varepsilon_0\mathbf{E}=-3.54\hat{a}_x-1.771\hat{a}_y \quad [nC/m^2]$
- $\begin{cases} D_N=|\mathbf{D}_P|=3.96[nC/m^2] \\ \therefore \rho_{S,P}=-3.96[nC/m^2] \end{cases}$
- Flux line Eq : $\dfrac{E_y}{E_x}=\dfrac{200y}{-200x}=-\dfrac{y}{x} \quad (=\dfrac{dy}{dx})$

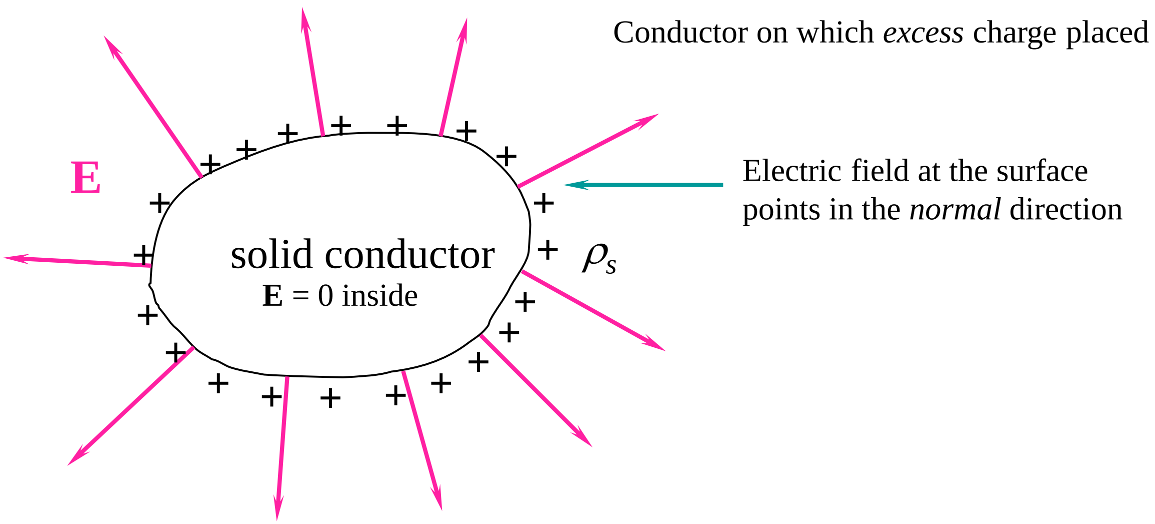
$$\frac{dy}{y}+\frac{dx}{x}=0$$

$\ln xy=C$, $xy=C'$, $at \quad P(2)\cdot(-1)=C_2=-2$

$\boxed{\therefore xy=-2}$ 인 쌍곡선

Lab. of Applied ElectroMagnetics

✓ Electrostatic Properties of Conductors



1. Charge can exist only on the surface as a surface charge density, ρ_s -- *not* in the interior.

2. Electric field *cannot* exist in the interior, nor can it possess a tangential component at the surface (as will be shown next slide).

3. It follows from condition 2 that the surface of a conductor is an *equipotential*.

5.5 전기영상법 Image Charge Method :

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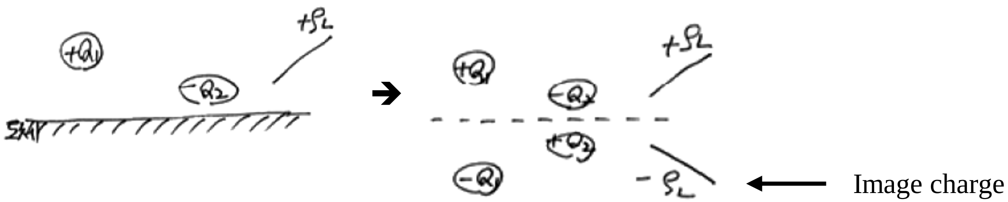
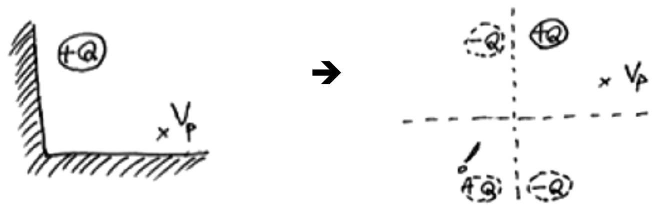
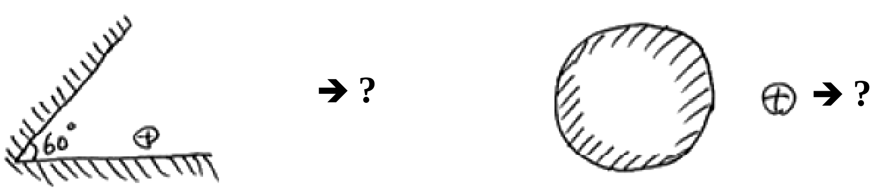
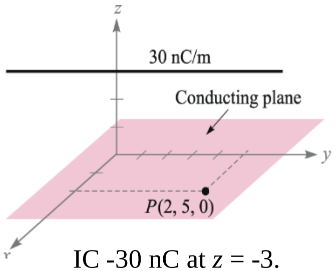
- 

- 

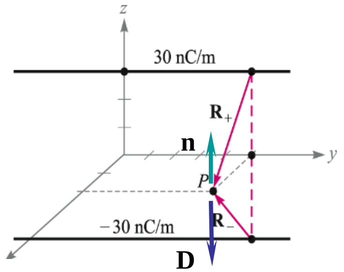
- Image charge 의 위치 , 개수 , 양



(Ex) Image Charge Method (The surface charge density on the conducting plane)



IC -30 nC at z = -3.



A 30-nC line charge lies parallel to the y axis at z = 3.

Surface Charge Density at P (2,5,0) =?

$$\mathbf{R}_+ = 2\mathbf{a}_x - 3\mathbf{a}_z$$

$$\mathbf{R}_- = 2\mathbf{a}_x + 3\mathbf{a}_z$$

$$\mathbf{E}_+ = \frac{\rho_L}{2\pi\epsilon_0 R_+}\mathbf{a}_{R+} = \frac{30\times 10^{-9}}{2\pi\epsilon_0\sqrt{13}}\,\frac{2\mathbf{a}_x - 3\mathbf{a}_z}{\sqrt{13}}$$

$$\mathbf{E}_- = \frac{30\times 10^{-9}}{2\pi\epsilon_0\sqrt{13}}\,\frac{2\mathbf{a}_x + 3\mathbf{a}_z}{\sqrt{13}}$$

$$\mathbf{E} = \frac{-180\times 10^{-9}\mathbf{a}_z}{2\pi\epsilon_0(13)} = -249\mathbf{a}_z \text{ V/m}$$

$$\mathbf{D} = \epsilon_0\mathbf{E} = -2.20\mathbf{a}_z \text{ nC/m}^2$$

$$\mathbf{D}\cdot\mathbf{n}\big|_s = \rho_s \qquad \mathbf{n} = \mathbf{a}_z$$

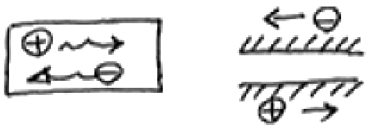
$$\mathbf{D}\cdot\mathbf{n} = -2.20\mathbf{a}_z\cdot\mathbf{a}_z = -2.20 \text{ nC/m}^2$$

진성반도체 (Intrinsic Semiconductor)
불순물반도체 (Extrinsic Semiconductor)

5.6 반도체

(1) 진성반도체 : • Ge , Si

• Carrier & Mobility : Carrier – electron , hole



$$\boxed{\sigma = -\rho_e \mu_e + \rho_h \mu_h}$$

μ_e : electron mobility
μ_h : hole mobility

m_e : electron 의 유효질량
m_h : hole 의 유효질량

✓ Ge : μ_e = 0.36 , μ_h = 0.17 , ρ_e = ρ_h = 3 $\boxed{\therefore \sigma = 1.6}$

Si : μ_e =0.12 , μ_h = 0.025 , ρ_e = ρ_h =0.0024 (300K) $\boxed{\therefore \sigma = 0.00035}$

• T ↑: 금속 : $\mu\downarrow$; $\sigma\downarrow$
반도체 : $\mu\downarrow + \rho\uparrow\uparrow$; $\sigma\uparrow$

(2) 불순물 반도체 :

• 진성 반도체 + 불순물 (Impurities) , Doping , Carrier 수 증가 , σ증가 , 조절

• Doping . 불순물을 10^{-7}첨가시 σ가 10^{5}배 증가 !

Donor 첨가 : 전자추가 (5가) : N형 반도체
Accepter첨가 : hole추가 (3가) : P형 반도체

N | P : Diode

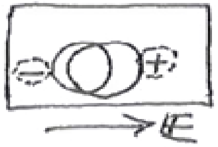
N | P | N : Transistor

• σ $[{}^{S}/_{m}]$: 부도체 – 수정 (10^{-17}) , 플라스틱 (10^{-7})
반도체 ~ 1
도체 – 10^{7} ~ 10^{8}

5.7 유전체의 성질

- 물질 내의 charge
  - 자유전하 多 : 도체
  - 속박전하 多 : 유전체 , 부도체, 절연체

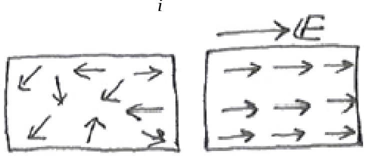
- 속박전하 (Bounded Charge) Q_b
  - ① 유극성 분자 (Polar Molecure) : 영구쌍극자 존재
  - ② 무극성 분자 : 전계가 있을 때만 분극하여 쌍극자 형성



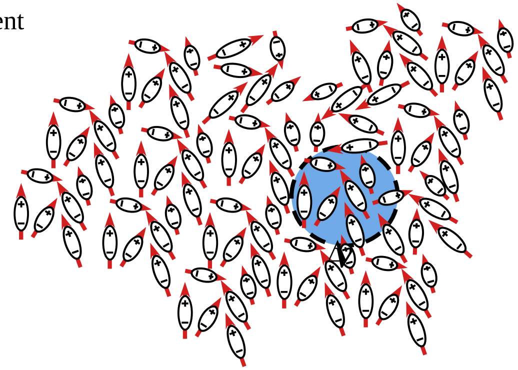
- 분극 (Polarization) P : 단위체적 당 쌍극자 모멘트. $\mathbf{P} = Q\mathbf{d}$, $\mathbf{P}_{total} = \sum_i \mathbf{P}_i$

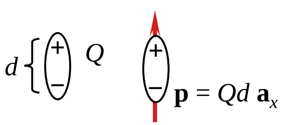
$$\mathbf{P} = \lim_{\Delta v \to 0} \frac{\sum_i \mathbf{P}_i}{\Delta v} \quad [C/m^2] \quad \text{: 분극(량)}$$

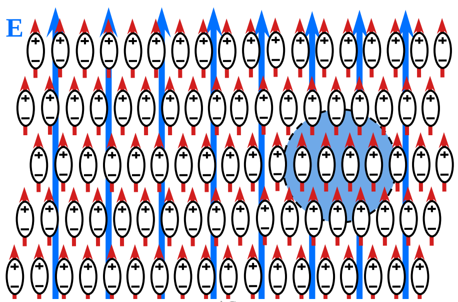
$$Q_b = -\int_s \mathbf{P} \cdot d\mathbf{S} \quad \text{: 속박전하}$$



- Dipole moment

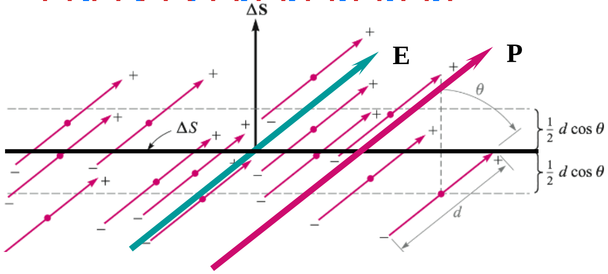






$$\Delta Q_b = nQd\cos\theta\,\Delta S$$

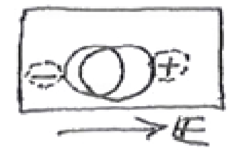
$$\Delta Q_b = nQ\mathbf{d} \cdot \Delta\mathbf{S}$$
$$= \mathbf{P} \cdot \Delta\mathbf{S}$$



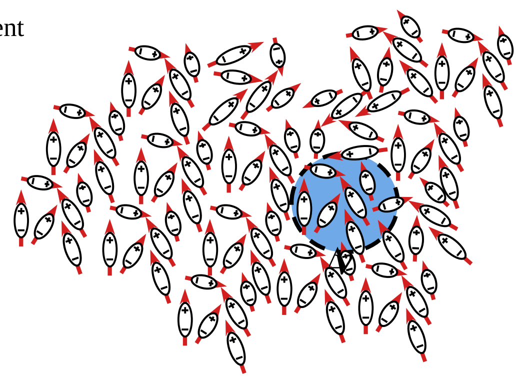
5.7 유전체의 성질

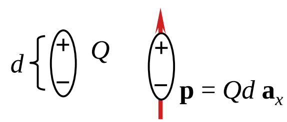
- 물질 내의 charge ⎧ 자유전하 多 : 도체
  ⎩ 속박전하 多 : 유전체 , 부도체, 절연체

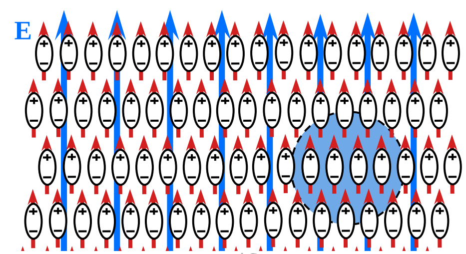
- 속박전하 (Bounded Charge) Q_b ⎧ ① 유극성 분자 (Polar Molecure) : 영구쌍극자 존재
  ⎩ ② 무극성 분자 : 전계가 있을 때만 분극하여 쌍극자 형성



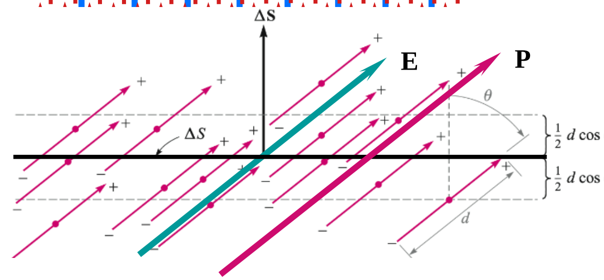
- Dipole moment





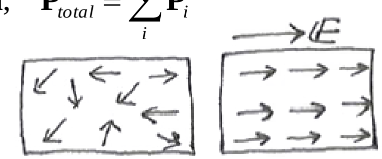


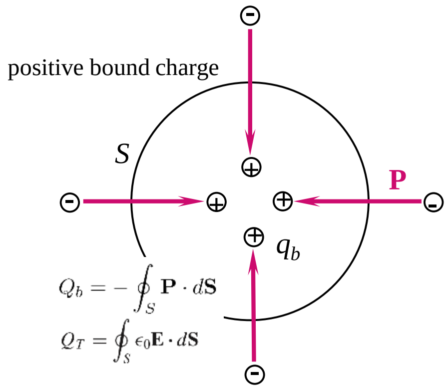
$$\Delta Q_b = nQd\cos\theta\Delta S$$
$$\Delta Q_b = nQ\mathbf{d}\cdot\Delta\mathbf{S} = \mathbf{P}\cdot\Delta\mathbf{S}$$

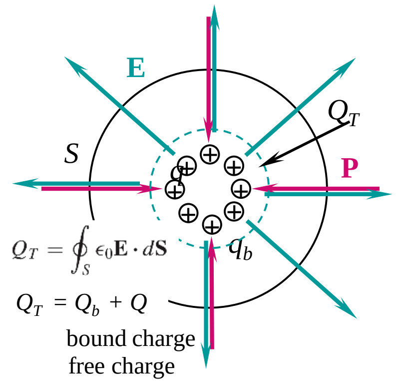


- 분극 (Polarization) P : 단위체적 당 쌍극자 모멘트. $\mathbf{P} = Q\mathbf{d}$, $\mathbf{P}_{total} = \sum_i \mathbf{P}_i$

$$\begin{cases} \mathbf{P} = \lim_{\Delta v \to 0} \dfrac{\sum_i \mathbf{P}_i}{\Delta v} \quad [C/m^2] & \text{: 분극(량)} \\ Q_b = -\int_s \mathbf{P}\cdot d\mathbf{S} & \text{: 속박전하} \end{cases}$$







$$Q_b = -\oint_S \mathbf{P}\cdot d\mathbf{S} \qquad Q_T = \oint_S \epsilon_0\mathbf{E}\cdot d\mathbf{S} = Q_b + Q$$

$$Q = Q_T - Q_b = \oint_S (\epsilon_0\mathbf{E}+\mathbf{P})\cdot d\mathbf{S} = \oint_S \mathbf{D}\cdot d\mathbf{S} \qquad \boxed{\mathbf{D} = \epsilon_0\mathbf{E}+\mathbf{P}}$$

Bound Charge: $Q_b = \int_v \rho_b\, dv = -\oint_S \mathbf{P}\cdot d\mathbf{S} \Rightarrow \nabla\cdot\mathbf{P} = -\rho_b$

Total Charge: $Q_T = \int_v \rho_T\, dv = \oint_S \epsilon_0\mathbf{E}\cdot d\mathbf{S} \Rightarrow \nabla\cdot\epsilon_0\mathbf{E} = \rho_T$

Free Charge: $Q = \int_v \rho_v\, dv = \oint_S \mathbf{D}\cdot d\mathbf{S} \Rightarrow \boxed{\nabla\cdot\mathbf{D} = \rho_v}$

* Total charge :

$$\begin{cases} Q_T = Q_b + Q = \oint_s \varepsilon_0\mathbf{E}\cdot d\mathbf{S} \ ! \\ Q = Q_T - Q_b = \oint_S (\varepsilon_0\mathbf{E}+\mathbf{P})\cdot d\mathbf{S} = \oint_S \mathbf{D}\cdot d\mathbf{S} \end{cases}$$

$\boxed{\therefore \mathbf{D} = \varepsilon_0\mathbf{E}+\mathbf{P}}$: Electric Flux D 를 만드는 것은 [외부에서 인가되는 전계의 세기 $\varepsilon_0\mathbf{E}$와 유전체에서 유기되는 분극 P의 합이다.

➢
$$\begin{bmatrix} Q = \int_v \rho_v dv & Q_b = \int_v \rho_b dv & Q_T = \int_v \rho_T dv \\ \nabla\ \mathbf{D} = \rho_f & \nabla\ \mathbf{P} = \ \rho_b & \nabla\ \varepsilon_0\mathbf{E} = \rho_T \end{bmatrix}$$

$$\begin{bmatrix} \rho_f, & \rho_b, & \rho_T \\ Q_f, & Q_b, & Q_T \end{bmatrix}$$? (known / unknown)

$$\begin{pmatrix} \boxed{Q = \int_v \rho_f dv, \quad \nabla\cdot\mathbf{D} = \rho_f} \\ Q_b = \int_v \rho_b dv, \quad \nabla\cdot\mathbf{P} = -\rho_b \\ Q_T = \int_v \rho_T dv, \quad \nabla\cdot\varepsilon_0\mathbf{E} = \rho_T \end{pmatrix}$$

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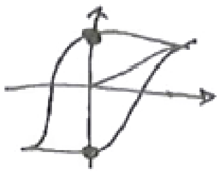
➢ 유전율 (Permittivity) ε :

- $\varepsilon_0 \mathbf{E} \rightarrow \mathbf{P}$, $\chi_e = \dfrac{\mathbf{P}}{\varepsilon_0 \mathbf{E}}$: 분극률 (Electric Susceptibility)
- $\mathbf{P} = \chi_e \varepsilon_0 \mathbf{E}$, $\mathbf{P} // \mathbf{E}$? { 등방성, 이방성 (Anisotropy) / Hysteresis, Flash Memory.



- $\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} = \varepsilon_0 \mathbf{E} + \chi_e \varepsilon_0 \mathbf{E} = (1 + \chi_e)\varepsilon_0 \mathbf{E} = \varepsilon_r \cdot \varepsilon_0 \mathbf{E} \equiv \varepsilon \mathbf{E}$

$\boxed{\therefore \mathbf{D} = \varepsilon\, \mathbf{E}}$

- $\varepsilon = \varepsilon_r \cdot \varepsilon_0 = (1 + \chi_e)\varepsilon_0$: 유전율 (Electric Permittivity)
- $\varepsilon = \dfrac{\mathbf{D}}{\mathbf{E}}$: E 에 대한 D 의 비율
- 물질고유상수. ε_r . Table

✓ $\boxed{\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}}$

- $Q = \int_v \rho_f \, dv = \oint_S \mathbf{D} \cdot d\mathbf{S}$
  - D : 자유전하
  - E :속박전하에 의한 효과는 ε 에 포함되어 있음
  - ε 에 따라 E 의 크기가 변화

χ_e : *susceptibility* $\mathbf{P} = \epsilon_0 \chi_e \mathbf{E}$

relative permittivity $\mathbf{D} = \epsilon_0 \mathbf{E} + \chi_e \epsilon_0 \mathbf{E} = (\chi_e + 1)\epsilon_0 \mathbf{E}$ $\epsilon_r = \chi_e + 1$

Permittivity : $\boxed{\mathbf{D} = \epsilon \mathbf{E}}$ $\epsilon = \epsilon_r \epsilon_0$

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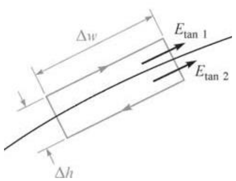
5.8 유전체의 경계조건

- cf. 도체의 경계조건 : $E_t = 0, \quad D_N = \rho_s \cong 0$

(Case 1) : 유전체 / 유전체

• E :



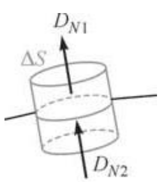
$$\left(\begin{array}{l} \oint \mathbf{E} \cdot d\mathbf{L} = 0 \\ E_{t1} \cdot \Delta w - E_{t2} \cdot \Delta w = 0 \\ \boxed{\therefore E_{t1} = E_{t2}} \quad (\mathbf{E}_1 - \mathbf{E}_2) \times \mathbf{n} = 0 \end{array} \right.$$

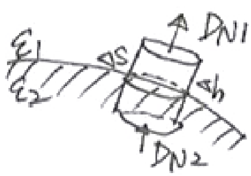
접선성분 연속 (E)

$$* \; E_{t1} = \frac{D_{t1}}{\varepsilon_1}, \quad E_{t2} = \frac{D_{t2}}{\varepsilon_2} \text{ 이므로}$$

$$\boxed{\frac{D_{\tan 1}}{D_{\tan 2}} = \frac{\epsilon_1}{\epsilon_2}}$$ D의 접선성분은 유전율의 비

• D :





$$\left(\begin{array}{l} \oint \mathbf{D} \cdot d\mathbf{S} = Q \\ D_{N1} \cdot \cancel{\Delta S} - D_{N2} \cdot \cancel{\Delta S} = \rho_S \cancel{\Delta S} \\ \boxed{\therefore D_{N1} - D_{N2} = \rho_S} \quad * \; \rho_S = 0 \text{ 일 경우} \\ \boxed{D_{N1} = D_{N2}} \quad (\mathbf{D}_1 - \mathbf{D}_2) \cdot \mathbf{n} = \rho_S \end{array} \right.$$

법선성분 연속 (D)

$$* \; \varepsilon_1 E_1 = \varepsilon_2 E_2 \text{ 이므로}$$

$$\boxed{\frac{E_{N1}}{E_{N2}} = \frac{\varepsilon_2}{\varepsilon_1}}$$ E의 법선성분은 유전율 비의 역수

➢ Sum : 유전체 경계조건 (E접선 , D법선 연속)

$$\left(\begin{array}{ll} \boxed{E_{t1} = E_{t2}} & D_{t1}/D_{t2} = \varepsilon_1/\varepsilon_2 \\ \boxed{D_{N1} = D_{N2}} & E_{N1}/E_{N2} = \varepsilon_2/\varepsilon_1 \end{array} \right)$$

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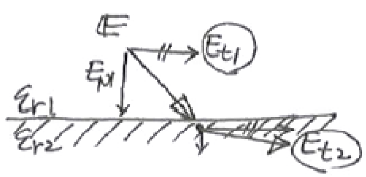
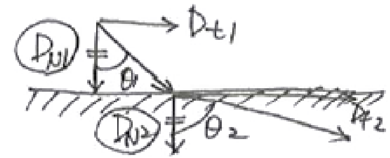
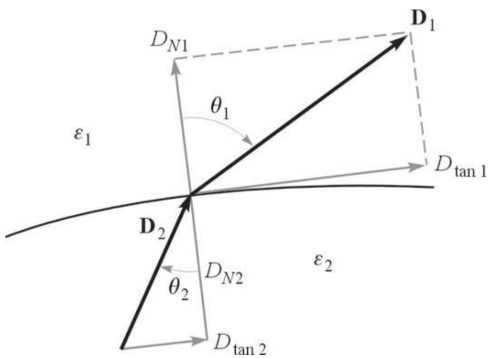
✓ <u>Loss Tangent</u>



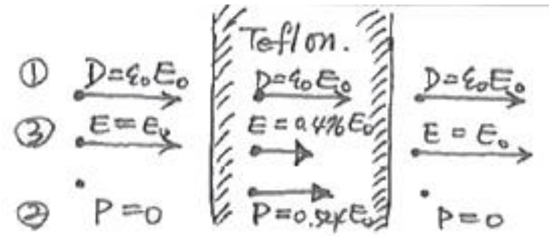




- $D_{N1} = D_{N2} \rightarrow D_1 \cos\theta_1 = D_2 \cos\theta_2$
- $\dfrac{D_{t1}}{D_{t2}} = \dfrac{D_1 \sin\theta_1}{D_2 \sin\theta_2} = \dfrac{\varepsilon_1}{\varepsilon_2} \rightarrow \varepsilon_2 D_1 \sin\theta_1 = \varepsilon_1 D_2 \sin\theta_2$ ➔ $\boxed{\dfrac{\tan\theta_1}{\tan\theta_2} = \dfrac{\varepsilon_1}{\varepsilon_2}}$

< Ex 5.5 > 테프론 (ε_r=2.1)

(χ_e=1.1)



(Case 2) : 유전체 / 도체

- 도체 내부 : $\mathbf{E} = \mathbf{0}$, $\mathbf{D} = \mathbf{0}$
- $$\begin{cases} \oint \mathbf{E} \cdot d\mathbf{L} = 0 & E_{t2} = 0 & \boxed{\therefore E_{t1} = 0} \\ \oint_S \mathbf{D} \cdot d\mathbf{S} = Q & D_{N2} = 0 & \boxed{\therefore D_{N1} = \varepsilon E_N = \rho_S} \end{cases}$$

(Case 3) : charge relaxation

- 도체 내부에서 발생한 charge의 표면도달시간
- $\mathbf{J} = \sigma \mathbf{E}$, $\nabla \cdot \mathbf{J} = -\dfrac{\partial \rho_v}{\partial t}$: 전하연속방정식

$$\nabla \cdot \mathbf{J} = \nabla \cdot (\sigma \mathbf{E}) = \nabla \cdot (\frac{\sigma}{\varepsilon} \mathbf{D})$$ 이므로

$$\nabla \cdot \mathbf{J} = \frac{\varepsilon}{\sigma} (\nabla \cdot \mathbf{J}) = -\frac{\varepsilon}{\sigma} \frac{\partial \rho_v}{\partial t}$$, $\nabla \cdot \mathbf{D} = \rho_v$ 이므로

$$\therefore \rho_v = -\frac{\varepsilon}{\sigma} \frac{\partial \rho_v}{\partial t}$$ 1'st order ODE. $\longrightarrow$ $\boxed{\rho_v = \rho_0 e^{-\frac{\sigma}{\varepsilon} t}}$

(ex) 증류수의 경우

(불량도체) $$\tau = \frac{\varepsilon}{\sigma} = \frac{80 \times 8.854 \times 10^{-12}}{2 \times 10^{-14}} = 3.54 \mu s$$

즉, 3.54 μs 동안 63%의 charge가 표면에 도달한다.