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Quantum Physics of
Semiconductor Materials
and Devices

Solutions Manual

Volume 1

2.1

(a) The 20°C resistivity of

$$\text{Silver: } \rho = 1.6 \times 10^{-6} \Omega \cdot \text{cm}$$

$$\text{Copper: } \rho = 1.68 \times 10^{-6} \Omega \cdot \text{cm}$$

Best conductors

$$\text{Teflon: } \rho \sim 10^{24} \Omega \cdot \text{cm}$$

Best insulator

So the ratio of resistivities is } $\sim \frac{10^{24}}{10^{-6}} \sim 10^{30}$.
of the order

(b)

Since Planck's constant $h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s}$,

and the magnitude of the electron charge $q = 1.6 \times 10^{-19} \text{ Coulomb}$,

$$\frac{h}{q^2} \sim 25898 \frac{\text{J}\cdot\text{s}}{(\text{Coulomb})^2} \sim 25898 \frac{\text{Coulomb}\cdot\text{Volt}\cdot\text{s}}{(\text{Coulomb})^2} \sim 25898 \frac{\text{Volt}}{\text{Amp}} \underbrace{\text{Ohm}}$$

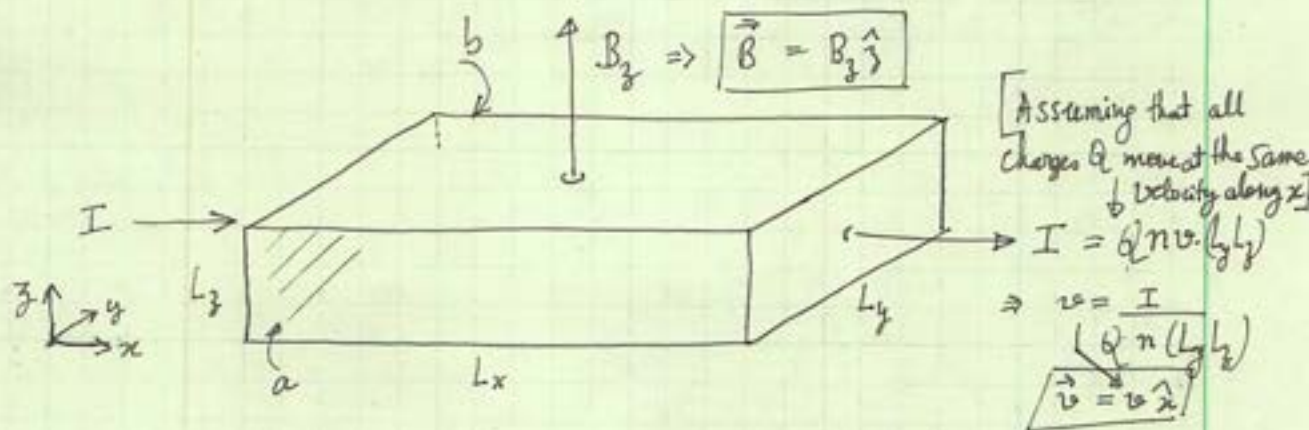
$$\Rightarrow \frac{h}{q^2} \sim 26 \text{ k}\Omega, \text{ and since the Bohr radius is } a_B^0 = 0.53 \text{ \AA},$$

$$\rho_Q = \left(\frac{h}{q^2}\right) \cdot (a_B^0) \cong (26 \text{ k}\Omega) \cdot (0.53 \text{ \AA}) \cong 1.37 \times 10^{-4} \Omega \cdot \text{cm}.$$

This value of electrical resistivity is $\sim 100\times$ larger than the resistivities of Silver and Copper at 20°C.

2.3

(a)



The Lorentz force on charge Q moving at a velocity \vec{v} is

$$\vec{F} = Q(\vec{E} + \vec{v} \times \vec{B}).$$

Using the boxed \vec{v} and \vec{B} from above,

$$\begin{aligned} \vec{F} &= Q(\vec{E} + \frac{I}{Q n (L_y L_z)} \cdot B_z \cdot \underbrace{\hat{x} \times \hat{z}}_{-\hat{y}}) \\ &= Q(\vec{E} - \frac{I B_z}{Q n (L_y L_z)} \hat{y}) \end{aligned}$$

The magnetic force in the \hat{y} -direction will be balanced by the force due to the electric field \vec{E} that develops due to charge accumulation on faces 'a' and 'b'. This is discussed further in

Chapter 25. The net force must be zero in steady state.

$$\Rightarrow \vec{F} = 0 = Q(\vec{E} - \frac{I B_z}{Q n (L_y L_z)} \hat{y}) \Rightarrow \vec{E} = \frac{I B_z}{Q n (L_y L_z)} \hat{y}$$

And the Hall voltage is $V_H = - \int_a^b \vec{E} \cdot \frac{d\vec{l}}{(dy) \hat{y}} = - \frac{I B_z}{Q n (L_y L_z)} \int_a^b dy = L_y$

$$\Rightarrow \boxed{V_H = \frac{-I B_z}{Q n L_z}}$$

2.3

(b)

Since the Hall voltage for charge Q is $V_H = -\frac{I B_z}{Q n L_z}$,

Writing the integrated sheet density as $n_s = n L_z$, if the

charge $Q = -q$ for an electron, $V_H = -\frac{I B_z}{(-q) n_s} = +\frac{I B_z}{q n_s}$.

If $Q = +q$ for holes, (or protons or positively charged ions),

$$V_H = \frac{-I B_z}{(+q) n_s} = -\frac{I B_z}{q n_s}.$$

Thus the sign of the Hall voltage that develops is an experimental measurement of the sign of the current-carrying particles.

(c)

The current density is $j_x = \frac{I}{L_y L_z}$

The lateral electric field is $E_y = \frac{V_H}{L_y} = -\frac{I B_z}{Q n L_z \cdot L_y}$

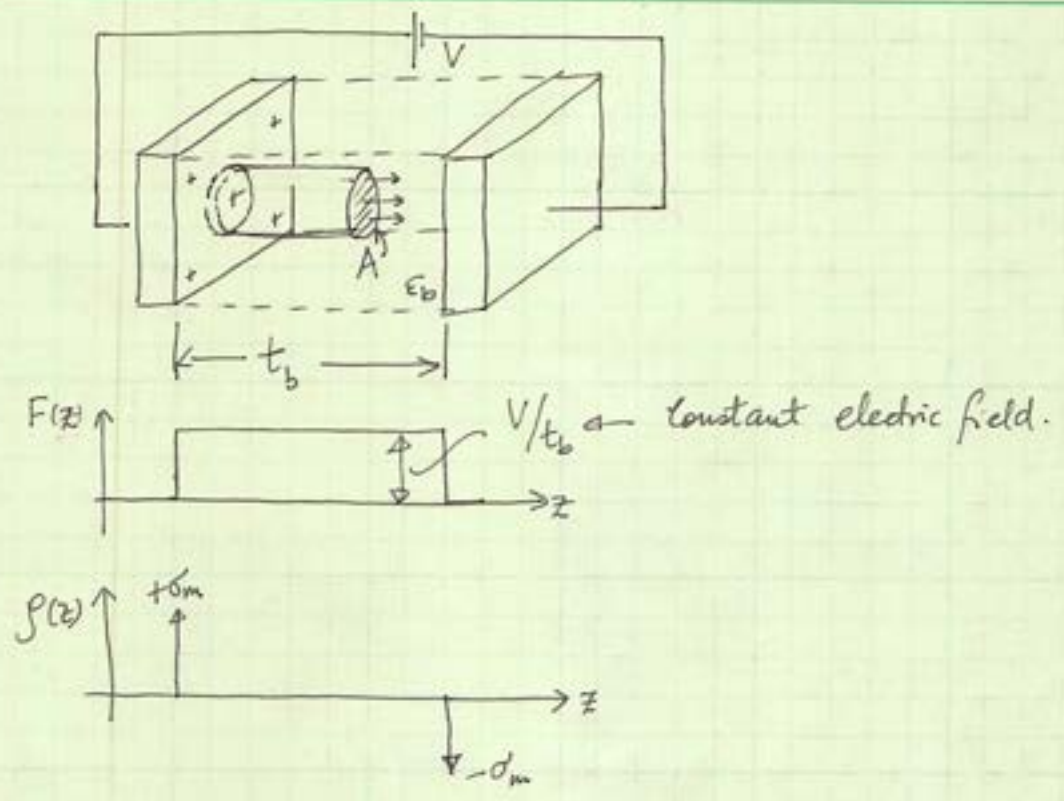
$$\Rightarrow R_H = \frac{E_y}{j_x \cdot B_z} = -\frac{I B_z}{Q n \frac{1}{3} L_y} \cdot \frac{L_y L_z}{I \cdot B_z} = -\frac{1}{Q n}$$

for electrons as the current-carrying particles, $Q = -q$

$\Rightarrow \boxed{R_H = \frac{1}{q n}}$, which is independent of the sample dimensions and the magnetic field.

2.4

(a)



The parallel-plate capacitor, the electric field profile $F(z)$, and the volume charge density $\rho(z)$ are sketched above.

The voltage source removes electrons from the left plate and moves them to the right plate. The net +ve charges of sheet density $+\sigma_m$ are formed on the inner face of the left plate, and equal and opposite $-\sigma_m$ on the inner face of the right plate. A constant electric field points to the right, from the +ve to negative charges.

Applying Gauss's law to the cylinder shown,

$$\oint \vec{E} \cdot d\vec{s} = Q_{\text{enclosed}} \quad \left\{ \begin{array}{l} \uparrow \\ \neq 0 \text{ inside the metal plate.} \\ \neq \text{ along } z, \text{ parallel to curved surfaces of the cylinder} \\ \neq \text{ perpendicular to face labeled 'A' } \end{array} \right. \Rightarrow \left. \begin{array}{l} \int_{\text{left}} \vec{E} \cdot d\vec{s} = 0 \\ \int_{\text{right}} \vec{E} \cdot d\vec{s} = 0 \\ \int_{\text{top/bottom}} \vec{E} \cdot d\vec{s} = 0 \\ \int_{\text{face A}} \vec{E} \cdot d\vec{s} = E \cdot A \end{array} \right\} \Rightarrow \left. \begin{array}{l} E_b E A = q \sigma_m A \\ E = \frac{q \sigma_m}{\epsilon_b} \end{array} \right\}$$

⑤

$$\text{For } F_{cr} \sim 10^7 \text{ V/cm}, \quad \sigma_{cr} \sim \frac{\epsilon_0 F_{cr}}{q} \sim \frac{10 \cdot (8.85 \cdot 10^{-12} \frac{\text{F}}{\text{cm}}) (10^7 \text{ V/cm})}{(1.6 \cdot 10^{-19} \text{ Coul})}$$

← assuming $10\epsilon_0$

$$\Rightarrow \underline{\sigma_{cr} \approx 5 \cdot 10^{13} / \text{cm}^2} \quad \leftarrow \text{Maximum carrier concentration that may be modulated by this insulator.}$$

Since the surface carrier concentration in most metals is of the order of $10^{14} - 10^{15} / \text{cm}^2$, typical insulators breakdown before modulating all this concentration, only a small fraction of the surface carriers can be modulated, not all.