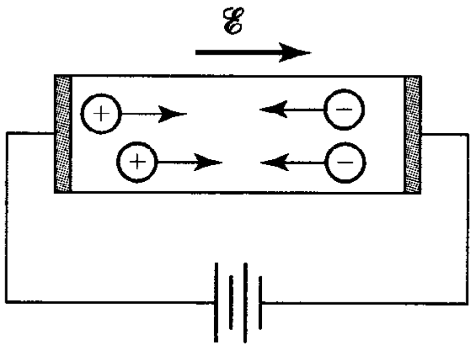
CARRIER TRANSPORT

Mechanisms

- Drift
- Diffusion

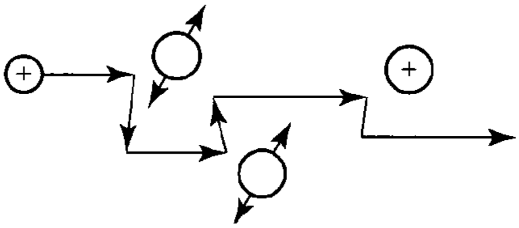
Drift

- Charged-particle motion in response to an applied electric field.
- Positive charges move in the direction of the electric field.
- Negative charges move in the opposite direction of the electric field.



Collisions

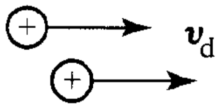
- Microscopic view



- Scattering due to
  - Phonon
  - Ionized impurity
  - Neutral impurity
  - Carrier
  - Piezoelectric

Average Velocity

- Macroscopic view → average or overall motion of the carriers.
- Drift velocity: v_d
- The drifting motion of the carriers arising in response to an applied electric field is actually superimposed upon the always-present thermal motion of the carriers.



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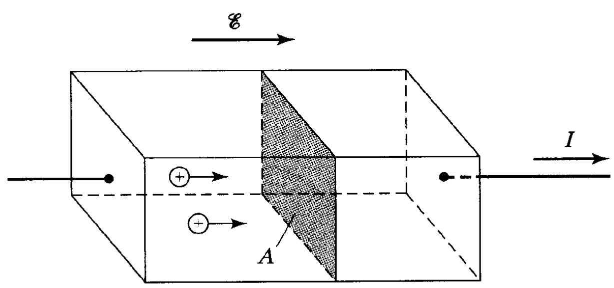
Drift Current

Consider a p-type semiconductor bar of cross-sectional area A.



I**:** The charge per unit time crossing an arbitrarily chosen plane of observation oriented normal to the direction of current flow

$\boldsymbol{v_d t}$**:** All holes this distance back from the v_d-normal plane will cross the plane in a time t

$\boldsymbol{v_d tA}$**:** All holes in this volume will cross the plane in a time t

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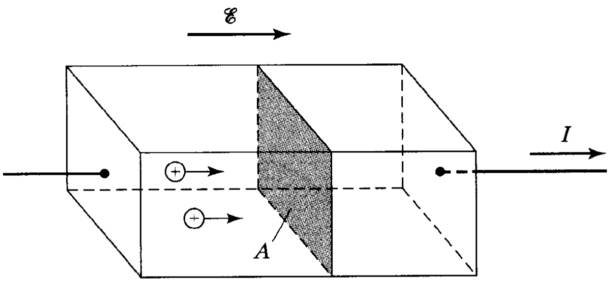
Drift Current

Consider a p-type semiconductor bar of cross-sectional area A.



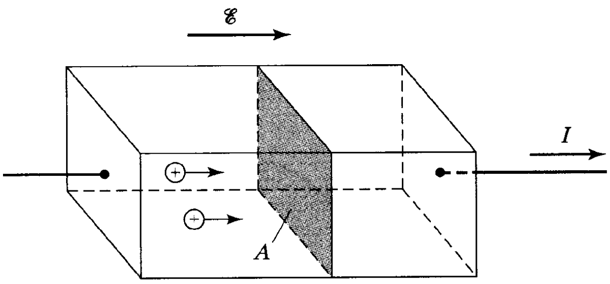
$pv_d tA$: Holes crossing the plane in a time t

$qpv_d tA$: Charge crossing the plane in a time t

$qpv_d A$: Charge crossing the plane per unit time

Drift Current

Consider a p-type semiconductor bar of cross-sectional area A.



$$i_{P|\text{drift}} = qpv_d A$$

$$\vec{J}_{P|\text{drift}} = qp\vec{v}_d$$

Relation with the Electric Field

$$\vec{v}_d = \mu_P \vec{\xi}$$

μ_p: Hole mobility

$$\vec{J}_{P|\text{drift}} = q\mu_p p\vec{\xi}$$

$$\vec{J}_{N|\text{drift}} = q\mu_n n\vec{\xi}$$

μ_n: Electron mobility

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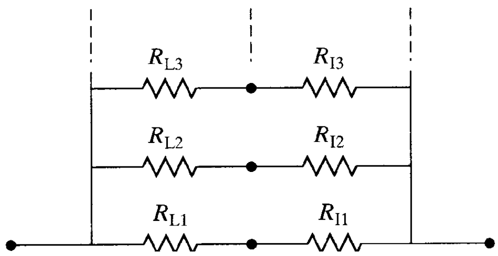
Mobility

$$\frac{1}{\mu_p} = \frac{1}{\mu_{Lp}} + \frac{1}{\mu_{Ip}} + \cdots$$

$$\frac{1}{\mu_n} = \frac{1}{\mu_{Ln}} + \frac{1}{\mu_{In}} + \cdots$$



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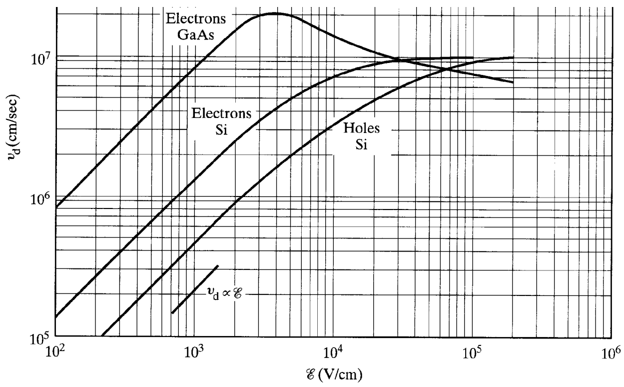
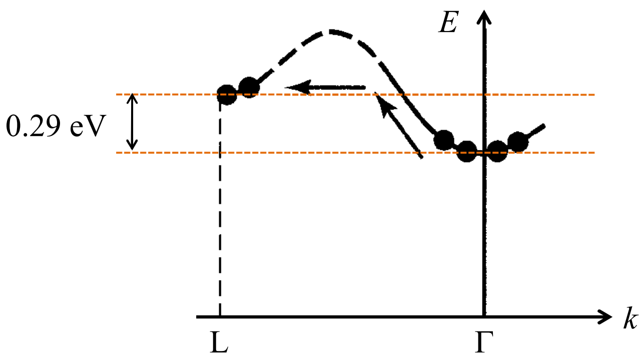
High Field/Narrow-Dimension Effects



- When the electric field exceeds 1–5×10^3 V/cm, the drift velocity is no longer directly proportional to the applied electric field.
- The peak in the GaAs curve is due to intervalley electron transfer.

Intervalley Carrier Transport



- L-valley is sparsely populated at room temperature.
- Γ-valley electrons may transfer to L-valley at high enough electric field.
- $m^*_{\text{L-valley}} >> m^*_{\Gamma\text{-valley}} \rightarrow$ drift velocity decreases.

Ballistic Transport

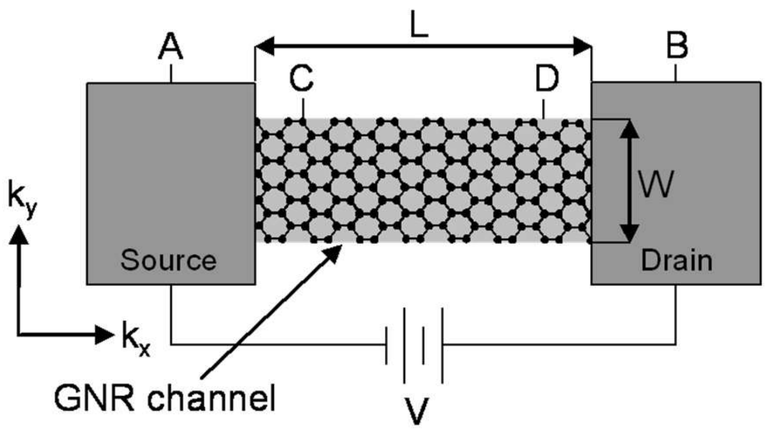
- Usually, $L >> l$.

  L: Distance through which the carriers travel

  l: Mean distance between scattering events

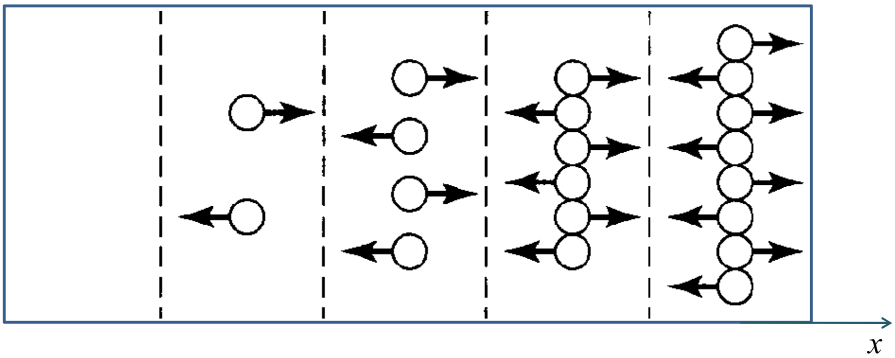
- Mobility/drift-velocity formalism begins to break down at $L \sim l$.
- At $L < l$, carriers may experience no scattering → projectiles similar to electrons in a vacuum tube → ballistic transport.
- **Note:** scattering probability increases with carrier velocity.

Graphene Nanoribbon FET



DIFFUSION

Concept



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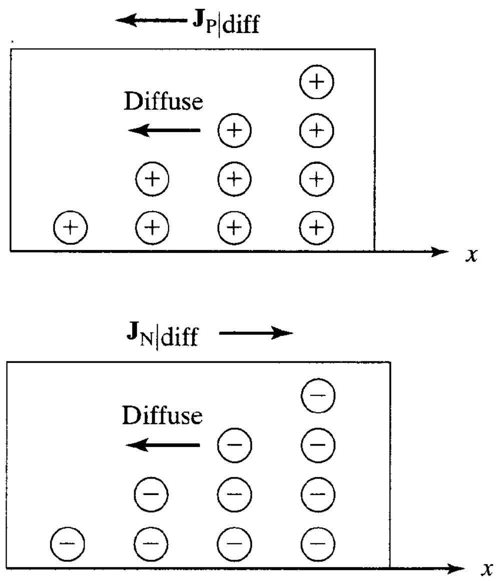
Concept



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Simplifications

- One-dimensional analysis.
- All carriers move with the same velocity.
- The distance traveled by carriers between collisions is fixed.

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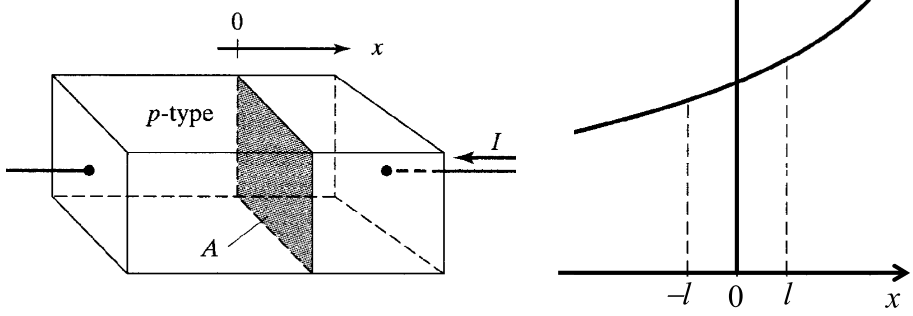
Derivation



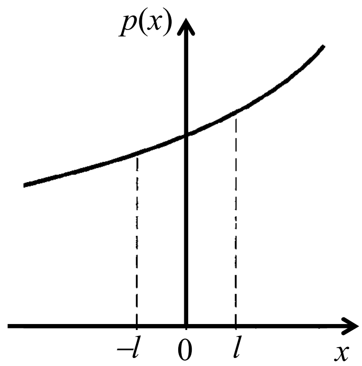
Derivation

$$\vec{p} = \begin{pmatrix} \text{Holes moving in the } +x \\ \text{direction which cross the} \\ x = 0 \text{ plane in a time } l/\bar{v} \end{pmatrix}$$

$$= \frac{A}{2}\int_{-l}^{0} p(x)dx$$

$$\vec{p} = \begin{pmatrix} \text{Holes moving in the } -x \\ \text{direction which cross the} \\ x = 0 \text{ plane in a time } l/\bar{v} \end{pmatrix}$$

$$= \frac{A}{2}\int_{0}^{l} p(x)dx$$



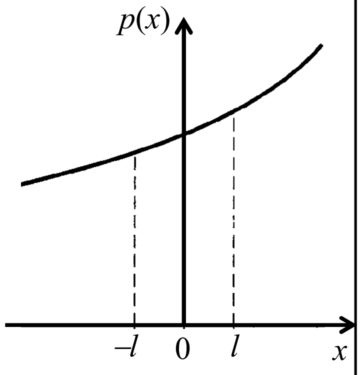
Diffusion

- Taking first two terms in the Taylor series expansion of $p(x)$.

$$p(x) \simeq p(0) + \left.\frac{dp}{dx}\right|_0 x + \cdots, \qquad -l \le x \le l$$

$$\vec{p} = \frac{A}{2}\int_{-l}^{0} p(x)dx = \frac{A}{2}\int_{-l}^{0}\left[p(0) + \left.\frac{dp}{dx}\right|_0 x \right]dx$$

$$= \frac{1}{2}Alp(0) - \frac{1}{2}A\left.\frac{dp}{dx}\right|_0 \frac{l^2}{2}$$



- Similarly

$$\overleftarrow{p} = \frac{1}{2}Alp(0) + \frac{1}{2}A\left.\frac{dp}{dx}\right|_0 \frac{l^2}{2}$$

Diffusion

- Net number of $+x$ directed holes:

$$\vec{p} - \overleftarrow{p} = -A\left.\frac{dp}{dx}\right|_0 \frac{l^2}{2}$$

- Net $+x$ directed charge:

$$Q_{P|\text{diff}} = q\left(\vec{p} - \overleftarrow{p}\right) = -\frac{1}{2}qA\frac{dp}{dx}\frac{l^2}{2}$$

- Net $+x$ directed charge per unit time:

$$I_{P|\text{diff}} = \frac{q\left(\vec{p} - \overleftarrow{p}\right)}{l/\bar{v}} = -\frac{1}{2}qA\bar{v}\,l\frac{dp}{dx}$$

Diffusion Current Density

- Current density:

$$J_{\mathrm{P|diff}} = -\frac{q\bar{v}\,l}{2}\frac{dp}{dx} = -qD_P\frac{dp}{dx}$$

$$D_p = \frac{\bar{v}\,l}{2}$$

D_p: Diffusion coefficient

$$J_{\mathrm{N|diff}} = -qD_N\frac{dn}{dx}$$

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Three Dimensions

$$J_{\mathrm{P|diff}} = -qD_{\mathrm{P}}\nabla p$$

$$J_{\mathrm{N|diff}} = qD_{\mathrm{N}}\nabla n$$

- Total current:

$$\vec{J} = \vec{J}_{\mathrm{N}} + \vec{J}_{\mathrm{P}}$$

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Displacement Current

- a.c. and transient conditions:

$$\vec{j}_D = \frac{\partial \vec{D}}{\partial t}$$

$$\vec{j} = \vec{J}_{\mathrm{N}} + \vec{J}_{\mathrm{P}} + \frac{\partial \vec{D}}{\partial t}$$

EEE 461

- ***We have finished EEE 461!***

- You can email me your questions/concerns at anis@eee.buet.ac.bd. Please use "EEE 461" in the subject line. I will try to answer.

Best Wishes for Your Graduation!

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