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Part 1: Introduction and Essentials of Solid-state Physics

Q: How do we describe the behavior of electrons constrained by an electrostatic potential?

Topics: What/why this course, fundamentals of quantum mechanics, particle in free space, particle in finite and infinite well and tunneling

EE 2104: Semiconductor Devices Fundamentals

EE, IIT Hyderabad

Shubhadeep B (shubhadeep@ee at iith)

Google classrooms code: hotnxfc3

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Administrative details

Welcome to EE2104: Semiconductor Device Fundamentals –

A Semiclassical Approach – From Atoms to Transistors ☺

Instructors: Dr. Shubhadeep B (shubhadeep@ee) and Dr. Oves B (oves.badami@ee)

TAs: Avanish, Lavanya, Krupakar, Ritvick and Akhil – Check on Google Classrooms

Google classrooms code: hotnxfc3: All announcements, lecture slides, assignments through classrooms – NOT email.

(A) Basic Modalities:

- Classroom ALH1, Slot-C Mon (11-12) Wed (10-11) Thu (9-10) – 3 credits (roughly 42-44 classes)
- Class hour (doubt clearing): Mon 12 – 1 pm in our office, after class

(B) Grading Policy (tentative, may change marginally):

- Attendance – 5%
- Assignments/In-class surprise quiz:25-35%
- Unit Tests (two or three exams) 65-75% {Formulae Sheet + Calculator}

(C) Reference Material/Textbooks:

Basics Textbooks:

1) Solid State Electronic Devices - B G. Streetman and S. K. Banerjee.

2) Introduction to Semiconductor Materials and Devices – M.S. Tyagi.

Advanced Textbooks

1) Advanced Semiconductor fundamentals – R. F. Pierret.

2) Physics of Semiconductor Devices – S. M. Sze and K. K. Ng

3) Fundamentals of Modern VLSI Devices – T. H. Ning and Y. Taur

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What/Why this course?

One line pitch:

Obj:-
study e^- (charge) transport in materials in the context of engineering semiconductor devices.

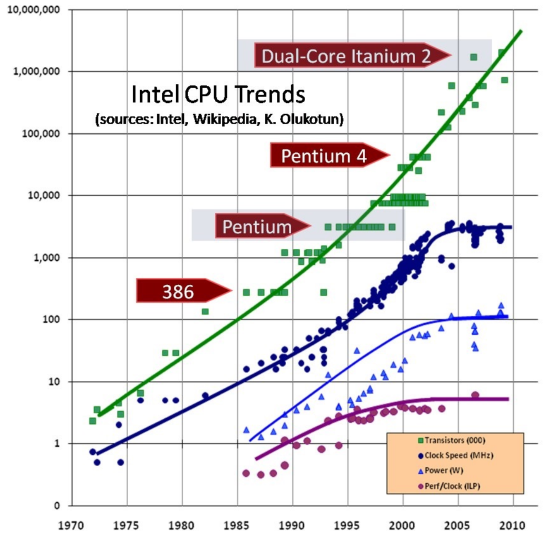
Two-line pitch:

Study of "tunable electrostatics barrier" engineers interesting charge transport.

Learning Outcome 1: *Understand how current semiconductor devices operate.*

A point of view: But why? Intel has already gone to 5 nm!

Myth #1 Is CMOS transistor scaling really a success? Questionable!



CMOS Scaling – Really??

Able to integrate exponentially more transistors – more functionality? ☺

Clock speed, power density and performance per CPU clock has stagnated. ☹

Time to acknowledge we have not solved all problems and created some!

Myth 2#: Semiconductor devices = CMOS logic

Learning Outcome 2: *Design devices for the future*

- Computation: Lower power
- EV technology: handle higher power
- Devices for AI/ML: neuromorphic
- Quantum computing (spintronics)
- Handle extreme environments
- Optoelectronics

and many more….

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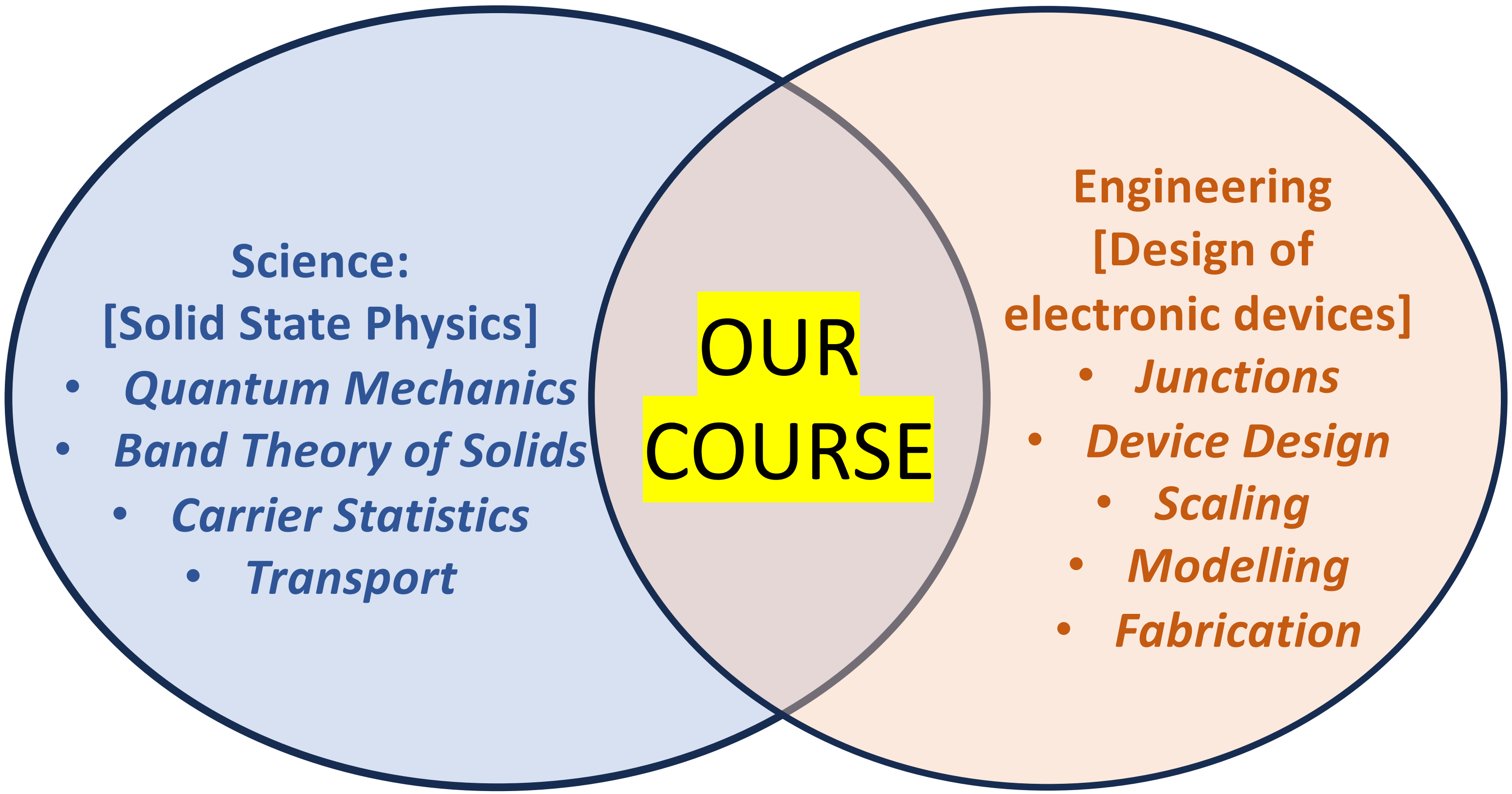
Approach of our Course – And a reflection of this field

This area (Semiconductor devices) is very unique:
It combines pure science and extreme engineering:
That is what we **love** about this area!



This course requires experienced handholding, cramming from textbook at last moment WILL NOT work!

Appeal: Come to class & follow the material.

Promise: You will have a great time! ☺

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Course Contents

Part 1: Semiconductor physics fundamentals (20-22 hrs)

- Intro/Motivation, Essentials of quantum mechanics (Wavefunction, Schrodinger's equation, particle in a potential well, tunneling) – Things you may know from +2/Modern Physics but with a new perspective.
- Band theory of solids (Qualitative formation of bands, Kroning Penney model, band gap, effective mass)
- Equilibrium carrier statistics (DOS, Fermi-Dirac Statistics)
- Non-equilibrium transport (Quasi-Fermi level, Transport: Drift/Diffusion, carrier continuity)

Part 2: Junctions and Devices (20-22 hrs)

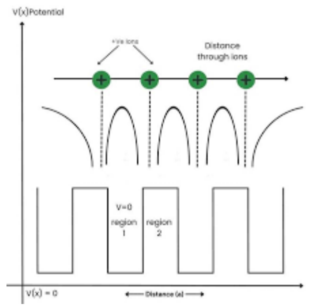
- *Semiconductor-Semiconductor: pn* Junctions: band diagrams, ideal and non-ideal I-V characteristics, basics of heterojunctions.
- Metal/ Semiconductor junctions (basic band diagrams and Ideal Schottky Mott theory)
- MOSCAPs (modes of operation, ideal and non-ideal CV characteristics)
- MOSFETs (long channel characteristics, short channel effects (SCE), device engineering to mitigate SCE)

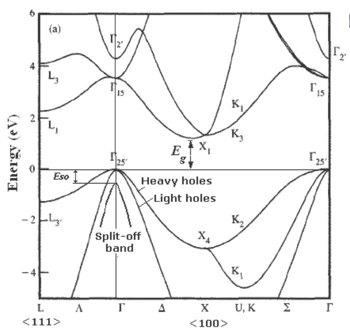
Approach of this course: ROADMAP

This Course: Semi-Classical Transport Modelling

Quantum mechanics

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V(\boldsymbol{x})\psi = E\psi$$





Transport over large length scales >> λ_{dB} (De-Broglie Wavelength of e-)

e- can be approximated to a 'particle'

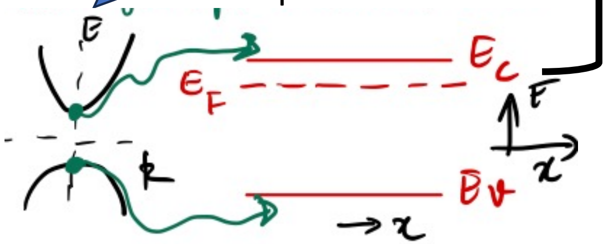
Approx 1

Particle Approx:
m* accelerated by 'E'

+ B.C.
V (end)

Approx 2

Near/Quasi Equilibrium:
Simple Band Picture



Semi-Classical

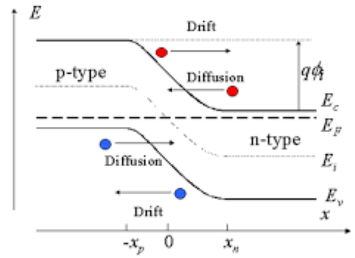
Electrostatics:
Poisson's Eqn

Drift-Diffusion

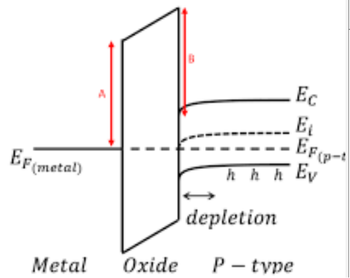
Carrier-Continuity

J_n, J_p

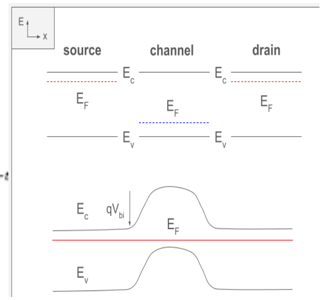
DIODE (p-n junction)



MOSCAP



MOSFET



Semiconductor Fundamentals (~20-22 hrs)

Junctions and Devices (20-22 hrs)

Essentials of Q Mech

Band Theory

Equilibrium carrier Stats

Non-Equ Transport

Where do we start from? (Motivation)

__Essentials__ of Quantum Mechanics and Solid-State Physics (Q: Why?)

Phenomenological basis
(Microscopic)

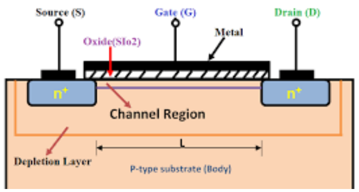
Practical basis
(Macroscopic)

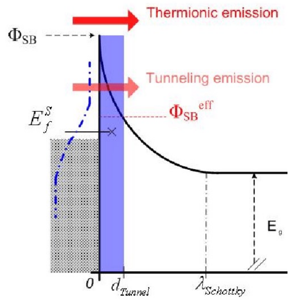
Behavior/Transport of electrons cannot by understood with classical laws!

- Is e- a particle/wave?
- What is the 'energy' of an electron? K.E. +P.E.
- How does the e- behavior change when in a crystal lattice?
- Do all e- have same energy in the lattice or is there a distribution.
- Transport of e- under a field.

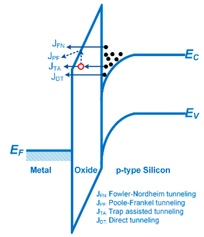
None of the modern devices can be explained/understood without QM principles
Becoming more relevant as all device dimensions are truly reaching atomic dimensions!

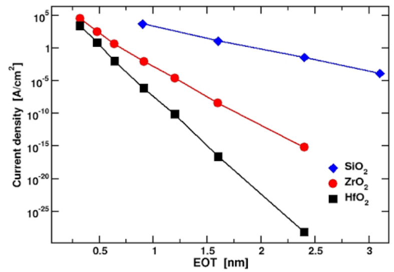
(a) Contacts ☺





(b) Gate ☹





Goal is not to study Solid state physics:
But gather necessary insights for the study of devices

Part 1:
Essentials of Quantum Mechanics

Q: How do we describe the behavior of electrons constrained by an electrostatic potential?

Topics: Wavefunction, particle in free space, particle in finite and infinite well and tunneling

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Why Quantum Mechanics?

Perplexing Question: How do you describe the nature of e-?

Classical model: Two ‘models’ of entities carrying energy

Particles

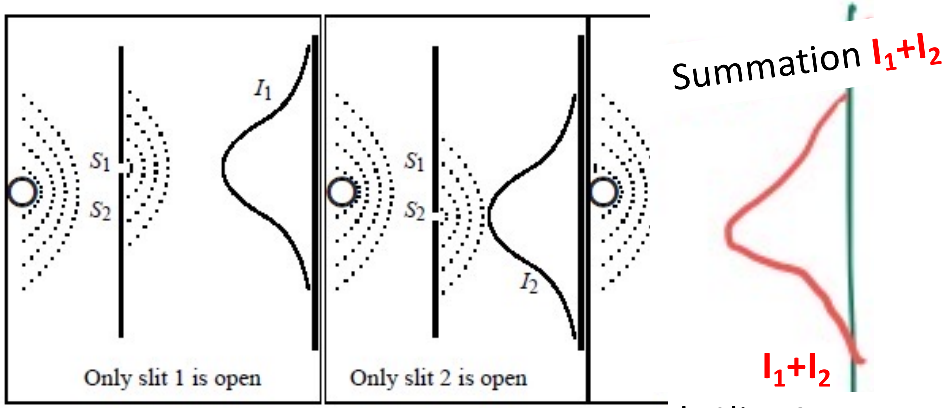
Waves

Localized! mass(m), momentum (p)

Non-localized! λ/ω, wavelength frequency

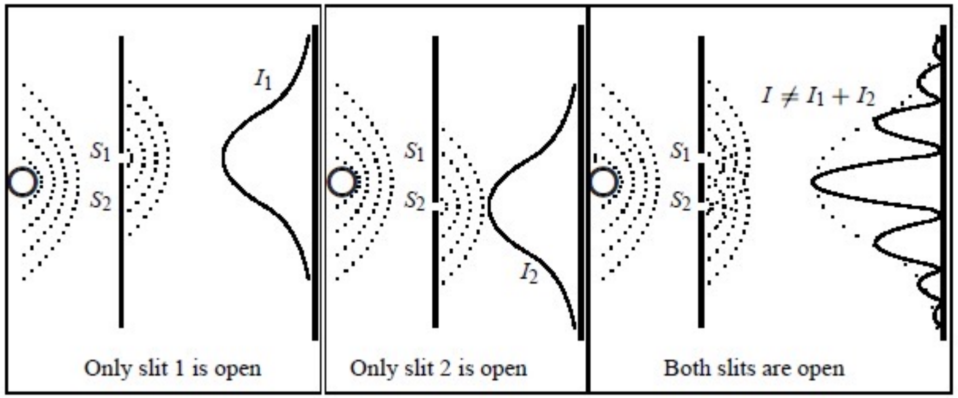
Functional definition/Operational test?

The Double Slit Experiment



Both Slits Open

I_{total} = I_1+I_2 **(Summation)**



Interference!

I_{total} = $I_1 + I_2 + 2\ I_1 I_2 \cos\theta$*

***θ -> Phase angle**

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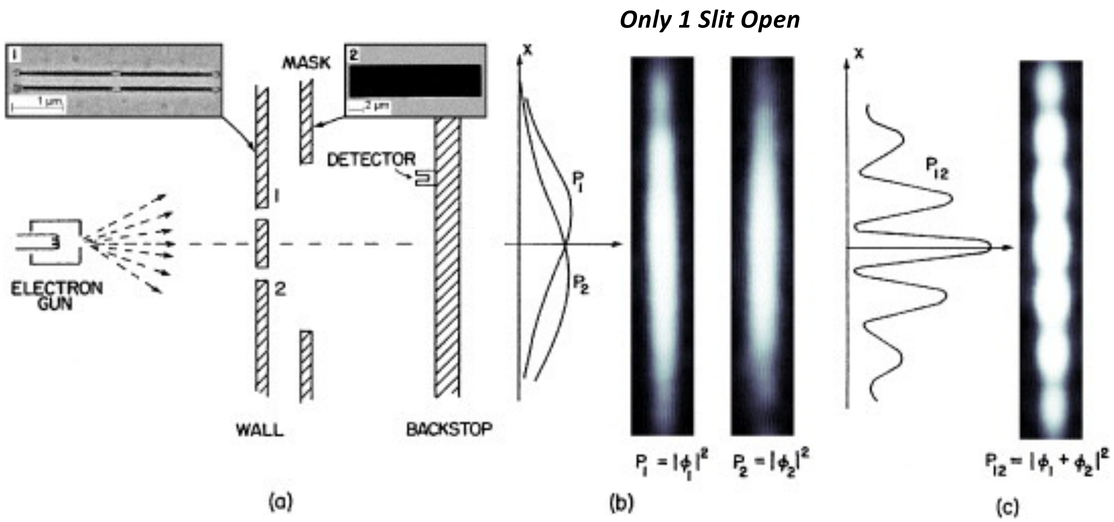
Double Slit Experiment on Electrons!

What do you expect with electrons? Electrons have $m_e = 10^{-31}$ Kg

Must behave like a Particle?

Surprise No.1



Electron produce an Interference pattern!
So e- can be described as waves?

Wait! Not so fast.

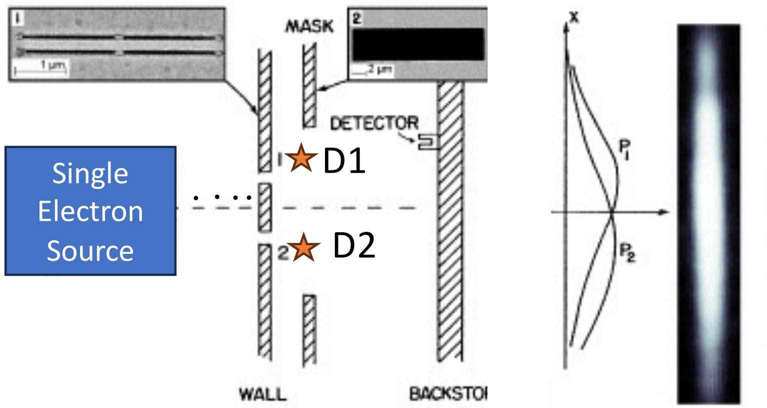
Refined Experiment:
Slow down: e- are sent one by one
Bunch of e- cannot be ‘interfere with each other.

Surprise No. 2

Initially random, eventually Interference! How?
Same e- passing through both slits?

Double Slit Experiment on Electrons!

Use detector D1 and D2 to find out if indeed e- is passing through Slit 1 or 2 or both.



I_1+I_2 with a detector

(a)

D1 and D2 glow ~50% time each
Half e- pass through S1 and other half S2

Surprise No. 3
Interference pattern disappears,
e- Start behaving like particles!

Back to Original Q: e- are particles or waves?

Is like asking: Horses are more like Unicorns or Centaurs?


=

OR

?

Answer: Electrons are real; particle and waves are fictitious (imaginary models of convenience)

Conundrum solved by Quantum mechanics:

e- are entities that obey quantum rules: they are characterized by *complex** wavefunction ψ(**r**,t) which indicates the probability of finding the particle at **r**,t

This probability 'collapses' when we make an observation/measurement.

Why should I believe this kooky theory: because all experiments say so!

*As in real and complex, not complicated

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Quantum Mechanics (One ring to bind them all) + $\Psi(r,t)$

unatum Mechanics

Planck's constant (h)

$*h = 6.626 \times 10^{-34}$ *J-s*

momentum

$p = \frac{h}{\lambda}$

particle ~ wave

wavelength

{De-Broglie equation}

*h in an eqn shows some Q Mech has been invoked

Feel for numbers: What is the λ_{db} for different 'massive' objects

$e^- \rightarrow m \sim 9 \times 10^{-31}$

$v = 10^5$ m/s

$\lambda = \frac{h}{mv} \approx 7.2$ nm

'particle + wave'

Ball $m \sim 0.1$ kg

$v \sim 50$ m/s

$\lambda = \frac{h}{mv} = \sim 10^{-32}$ m

"almost a particle"

$\Psi(\vec{r}, t) \equiv$ Wave function encapsulates all "measurable" info

1) { physically $\Rightarrow \Psi\Psi^* = |\Psi|^2$ Probability of finding "object"

2) ↳ but collapses to a single value when measured HOW?

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QM Operators

Quantum Mechanical operators operate on one wavefunction to "extract / measure" information

Only 3 operators are of Interest to us :- {Simplicity 1D only}

#1) Momentum operator, $\hat{p}_x = \underbrace{\frac{\hbar}{i}\frac{\partial}{\partial x}}_{\text{operator}}\psi$ wave function

#2) Energy Operator, $\hat{E} = -\frac{\hbar}{i}\frac{\partial \psi}{\partial t}$ } Total energy of system

#3) Potential Energy Operator $= \underbrace{V(x)}_{\text{potential profile}}\psi$

#4 Kinetic Energy Operator $= \hat{p}_x^2/2m = \frac{1}{2m}\frac{\hbar^2}{(i)^2}\frac{\partial^2 \psi}{\partial x^2} = -\frac{\hbar^2}{2m}\frac{\partial^2 \psi}{\partial x^2}$

We have, total, kinetic & potential Energy → What next?

Clarification:

In purple (operator) $\hat{p}$

In Green (Wave function) ψ

Momentum $p\psi = \hat{p}\psi$

{phy Qty}

Clarification (K.E. Operator):

$(\hat{p})^2 \rightarrow \frac{\partial}{\partial x}\left(\frac{\partial}{\partial x}\right) = \frac{\partial^2}{\partial x^2}$

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Schrödinger wave equation

Energy balance equation :- K.E + P.E = T.E

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi(x,t)}{\partial x^2} + V(x)\,\psi(x,t) = -\frac{\hbar}{i}\frac{\partial \psi(x,t)}{\partial t}$$

Simplification → THIS COURSE:- consider time-independent / steady-state equation.

$$\boxed{-\frac{\hbar^2}{2m}\frac{\partial^2\psi(x)}{\partial x^2} + V(x)\,\psi(x) = E\,\psi(x)} \Rightarrow \hat{H}\psi = E\psi$$

E ← constant

$\hat{H} \equiv$ HAMILTONIAN OPERATOR.

$$= -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x)$$

ALL OF SOLID STATE PHYSICS.

→ solve* scrodinger equation for different $V(x)$ find $\psi(x)$, E

* 1) Correct boundary conditions 2) Preserve physical $\psi(x)$

$\psi(x)$ & $\psi'(x)$ is continuous and does not "blow up"

Solving SCE in V(x)= 0 – free particle

Profile #0 {Basic} particle in free space, no confining Potential

$V(x)=0 \quad -\infty < x < \infty$

SOLVE SCHRODINGER EQUATION

$$-\frac{\hbar^2}{2m}\frac{\partial^2 \psi(x)}{\partial x^2} + 0\,\psi(x) = E\,\psi(x)$$

constant {steady-state}

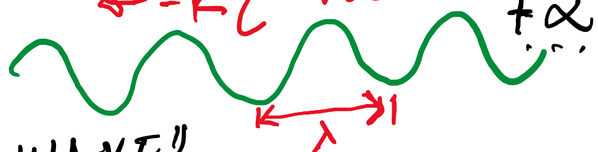
$$\frac{\partial^2 \psi(x)}{\partial x^2} = -\boxed{\frac{2mE}{\hbar^2}}\,\psi(x) \rightsquigarrow k^2$$

$$\psi_{\pm}(x) = A_{\pm}\, e^{\pm ikx}, \text{ where } k=\sqrt{\frac{2mE}{\hbar^2}}$$

$$\psi(x) = A^* \sin(kx) + B^* \cos(kx)$$

$k = 2\pi/\lambda \quad \rightarrow +k,\ \leftarrow -k$ {PROPAGATION VECTOR}

$\psi_{+}(x)$ $-\infty$ ... $+\infty$



"PLANE WAVE"

Q:- What is the location of this "particle" in 1D space:- EVERYWHERE!

Q:- what is the momentum

$$\hat{p}\psi = \frac{\hbar}{i}\frac{\partial e^{ikx}}{\partial x} = \hbar k\,\psi(x) \qquad p=\hbar k$$

What does this indicate? Heisenberg uncertainity.

$$\Delta p = 0 \Rightarrow \Delta x = \infty$$

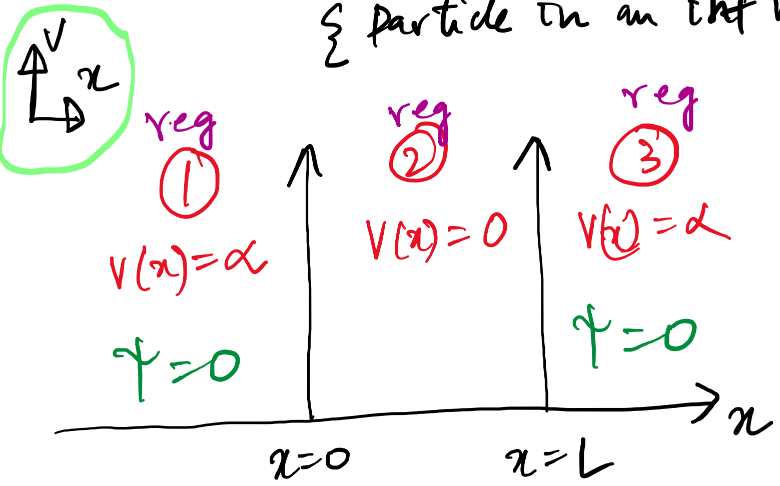
Very Imp: k physical meaning (a) propagation vector (b) momentum/energy

Homework/Assignment: Energy of plane wave - E vs. k relation?

A*,B* are complex numbers!

Solving SCE in V(x) – *Particle in a box (infinite well)*

Profile #1 {Particle in a 1-D box}
{Particle in an inf well}



1-D Box of length L

$$V(x) = \infty \quad x<0,\ x>L$$
$$\quad\;\; = 0 \quad 0<x<L$$

Task :- Find $\psi(x)$ & E
{wave function} {Energy}

Approach: Solve Schrödinger equation with correct boundary cond.

#1 Regions 1 & 3 $V(x) = \infty$

In other words, particle cannot exist in regions 1 & 3! $|\psi|^2 = \psi = 0$

#2 Region 2 $V(x) = 0$

S.C.E becomes:-

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi(x)}{\partial x^2} = \overset{\text{constant \{steady state\}}}{E}\,\psi(x)$$

$$\frac{\partial^2\psi(x)}{\partial x^2} = \frac{-2mE}{\hbar^2}\psi(x)$$

Solving SCE in V(x) – ***Boundary Conditions***

Is of the form of :-

$$\frac{d^2 y(x)}{dx^2} = -k^2 y(x) \Bigg\} \overset{\text{Well known solution}}{y(x) = A\sin(kx) + B\cos(kx)}$$

$$\therefore \frac{\partial^2 \psi(x)}{\partial x^2} = \frac{-2mE}{\hbar^2}\psi(x)$$ solutions are :-

$$\psi(x) = A\sin(kx) + B\cos(kx) \quad -(1)^*$$

where $k = \sqrt{\frac{2mE}{\hbar^2}}$ const

Next, find A, B, and 'E' and how?

Remember const. A, B can be complex

Remember (1) $\psi(x) = 0$; $x \le 0$ & $x \ge L$

(2) $\psi(x), \psi'(x)$ is continuous for all 'x'

$$\therefore \psi(x=0) = \psi(x=L) = 0$$

$\boxed{\text{3 unknowns } A, B, E;\ 2 \text{ equations :-C}}$

Substituting in (1)*

$$0 = A\sin(0) + B\cos(0) \quad \{@\ x=0\}$$

$$\boxed{B=0}$$

$$0 = A\sin(kL) \quad \{@\ x=L\}$$

since E, k unknown

'A' cannot be found!

But $A \neq 0$ $\sin(kL) = 0$

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Solving SCE in V(x) – ***Quantization and Normalization***

$kL = n\pi$, $n \in \mathbb{I}$ {Integer} $\sin(n\pi) = 0$

1, 2, 3...

$\boxed{k = n\pi/L}$

$\sqrt{\frac{2mE}{\hbar^2}}\, L = n\pi$; $E = \frac{n^2\pi^2\hbar^2}{2mL^2}$

$$\boxed{E_n = \frac{n^2 h^2}{8mL^2} \quad n \in 1, 2, 3 \ldots}$$

Insights:

#1) $k_n \propto n$ & $E_n \propto n^2$ discretized "Quantized"!!

#2) Infinite solutions. $n \in 1, 2, 3 \ldots$

#3) Comparison with free particle.
↳ e^{ikx} any value of 'k' & 'E' allowed!
"CONTINUUM OF STATES"

VS.

Particle (constrained) in a BOX ⇒ E_n, k_n {QUANTIZED / DISCRETIZED STATES}

WHY? ⇒ BOUNDARY CONDITIONS!!!

$\psi(x) = A \sin\left(\frac{n\pi}{L} x\right)$

How to find ?

Remember $|\psi(x)|^2 \Rightarrow$ probability of finding particle

$\int_{-\infty}^{\infty} |\psi(x)|^2 = 1 \Rightarrow \int_0^L |\psi(x)|^2 = 1$ {Wave func. normalisation}

$\int_0^L A^2 \sin^2\left(\frac{n\pi x}{L}\right) = 1 \Rightarrow A = \sqrt{\frac{2}{L}}$

$$\boxed{\psi_n(x) = \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi x}{L}\right); \; E_n = \frac{n^2 h^2}{8mL^2}} \quad n \in 1, 2, 3 \ldots$$

Seen this anywhere else in physics?

" STANDING WAVES"

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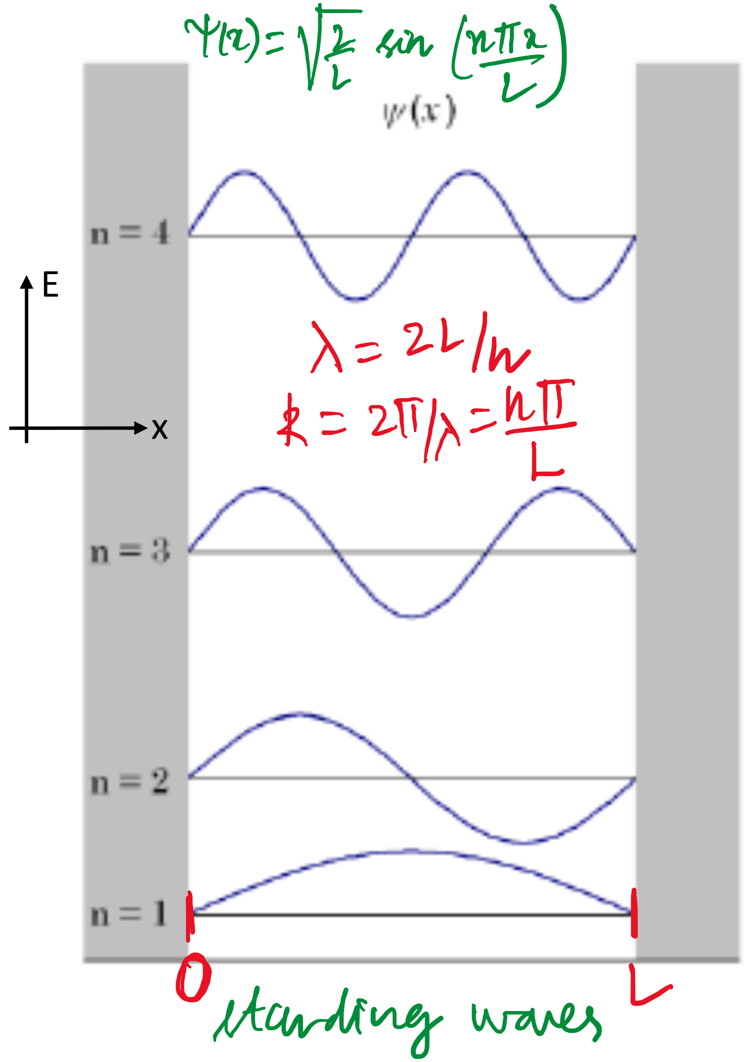
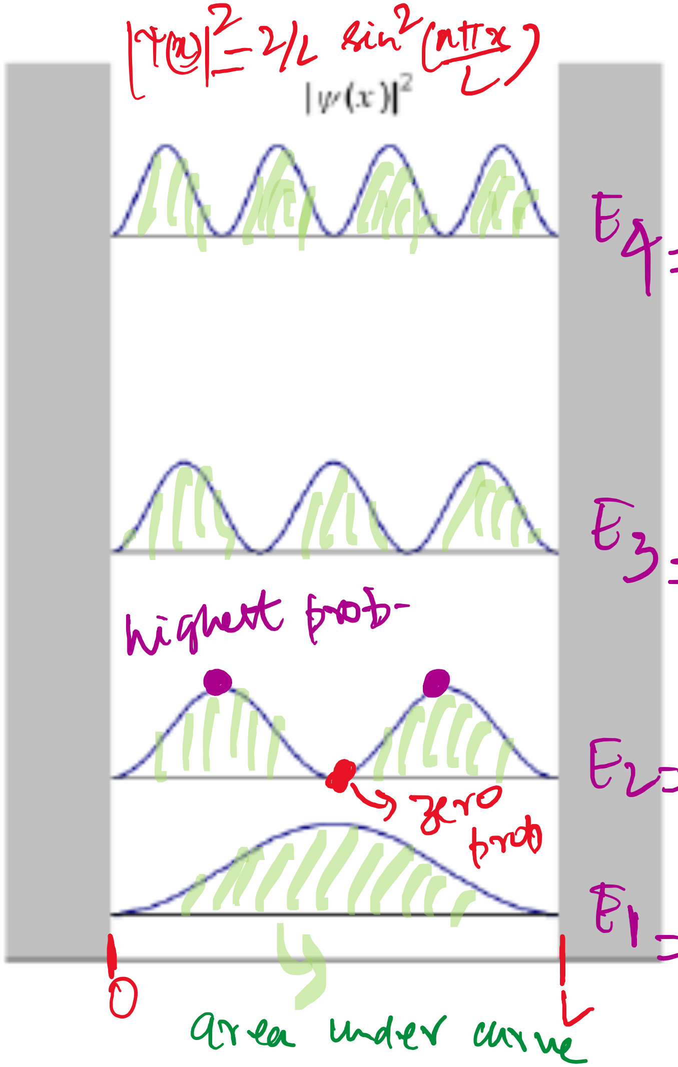
Solving SCE in V(x) – ***Visualization***





$E_4 = \frac{16\, h^2}{8mL^2}$

$E_3 = \frac{9\, h^2}{8mL^2}$

$E_2 = \frac{4\, h^2}{8mL^2}$

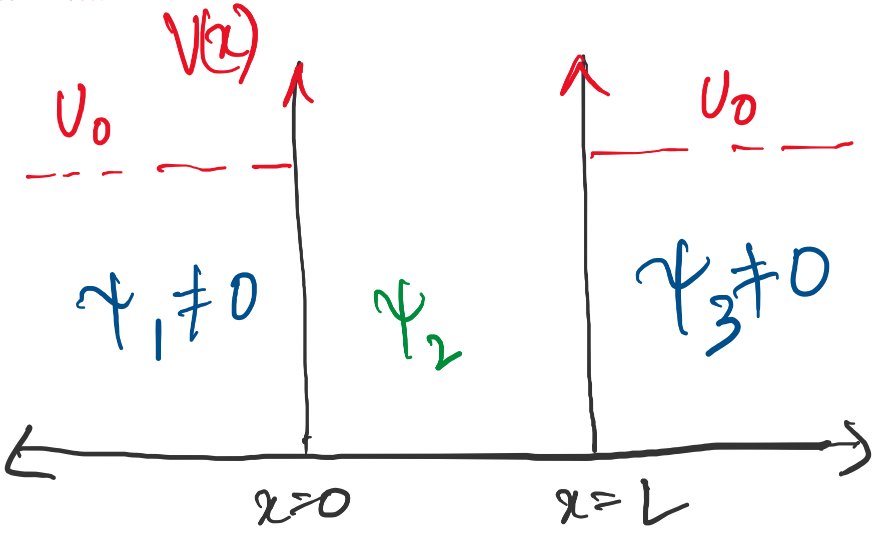
$E_1 = \frac{1\, h^2}{8mL^2}$

"Classical" vs Quantum Regime
Will a charged tennis ball show discrete Energy states?

A feel for numbers.
considering electron.
$\frac{h^2}{8m} \simeq 6e{-}38$

"m & L" should be very small to "measure" Quantization Effects!

V(x)#2: Particle in a finite well (closer to an atom!)



$V(x) = V_0$ $\quad V(x) = 0$ $\quad V(x) = V_0$

Q1) What remains same from previous case.

↳ Scrodinger's equation & general form of solution {Region ②}

$\psi_2(x) = A_2 \sin(kx) + B_2 \cos(kx)$

NOT ~~A sin(kx)~~ ↳ ①

Q2) What are the things that change?

1) $\psi_1, \psi_3 \neq 0 \rightarrow$ Solutions to SCE is possible!

$V_1, V_3(x) = V_0$ {finite}.

Q2a) Will this have infinite Quantized States?

NO!! ↳ For $E > V_0$ can escape {FREE CONTINUUM}.

↳ for $\boxed{E < V_0 \text{ "BOUND QUANTIZED STATES"}}$

SCE in regions ①,③ $-\frac{\hbar^2}{2m}\frac{\partial^2 \psi(x)}{\partial x^2} + V_0\psi(x) = E\psi(x)$

$$\frac{\partial^2\psi(x)}{\partial x^2} = -\boxed{\frac{2m(E-V_0)}{\hbar^2}}\psi(x) \rightarrow \alpha^2 < 0;\ \alpha \rightarrow \text{imaginary}.$$

{For $E < V_0$}.

No longer "propagating wave" but an exponential

$$\left.\begin{aligned}\psi_1(x) &= A_1 e^{\alpha x} + B_1 e^{-\alpha x}\\ \psi_3(x) &= A_3 e^{\alpha x} + B_3 e^{-\alpha x}\end{aligned}\right\}\ ②$$

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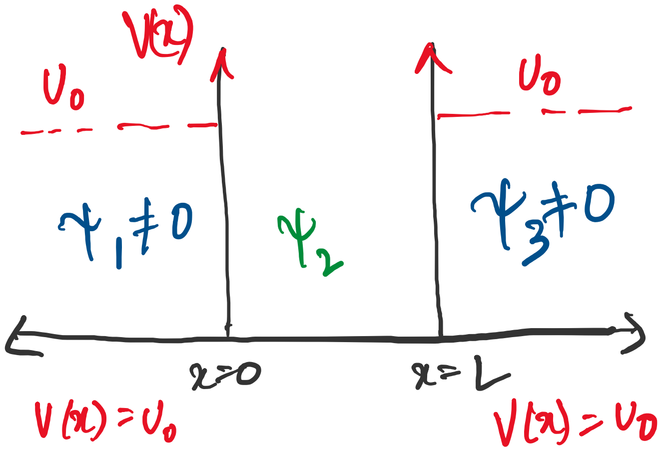
V(x)#2: Particle in a finite well – Boundary Conditions



$\psi_1(x) = A_1 e^{\alpha x} + B_1 e^{-\alpha x}$

$\psi_2(x) = A_2 \sin(kx) + B_2 \cos(kx)$

$\psi_3(x) = A_3 e^{\alpha x} + B_3 e^{-\alpha x}$

7 unknowns :-

$A_i, B_i \{i = 1,2,3\}, E$

For free state $\{E > V_0\} \Rightarrow$ plane wave continuum

For bound states $\{E < V_0\}$ SIX BOUNDARY CONDITION

1. $\psi_1(-\infty) = 0$ 2. $\psi_3(\infty) = 0$ ψ cannot blow up

3. $\psi_1(0) = \psi_2(0)$ 4. $\psi_2(L) = \psi_3(L)$ ψ continuous

5. $\psi_1'(0) = \psi_2'(0)$ 6. $\psi_2'(L) = \psi_3'(L)$ ψ' cont. ψ diff

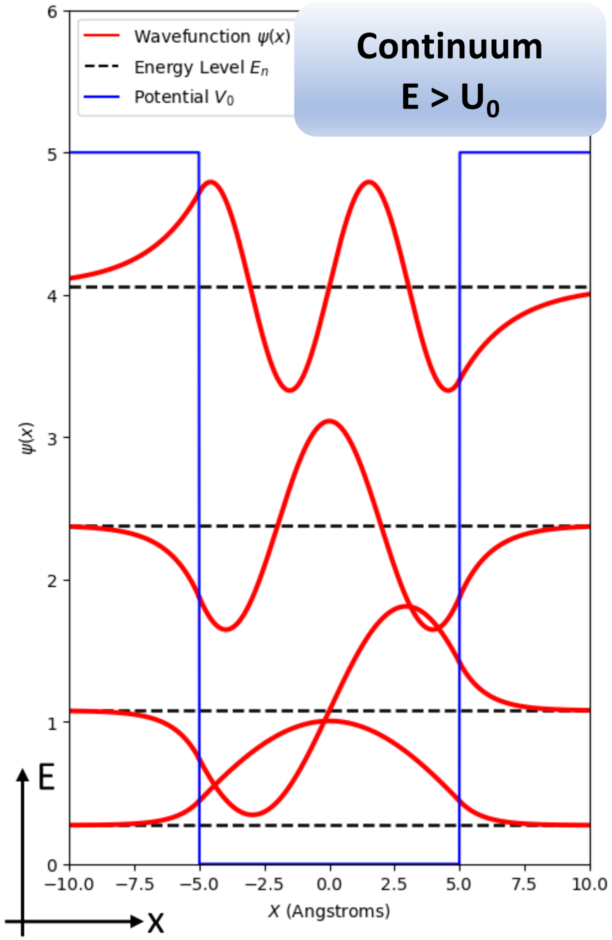
7. $\int_{-\infty}^{+\infty} |\psi(x)|^2 dx = 1$

All the unknowns can be found out

WE will focus on visual represent of bound states.

Visualizing wave function in finite potential well

L = 1 nm; m= m_e



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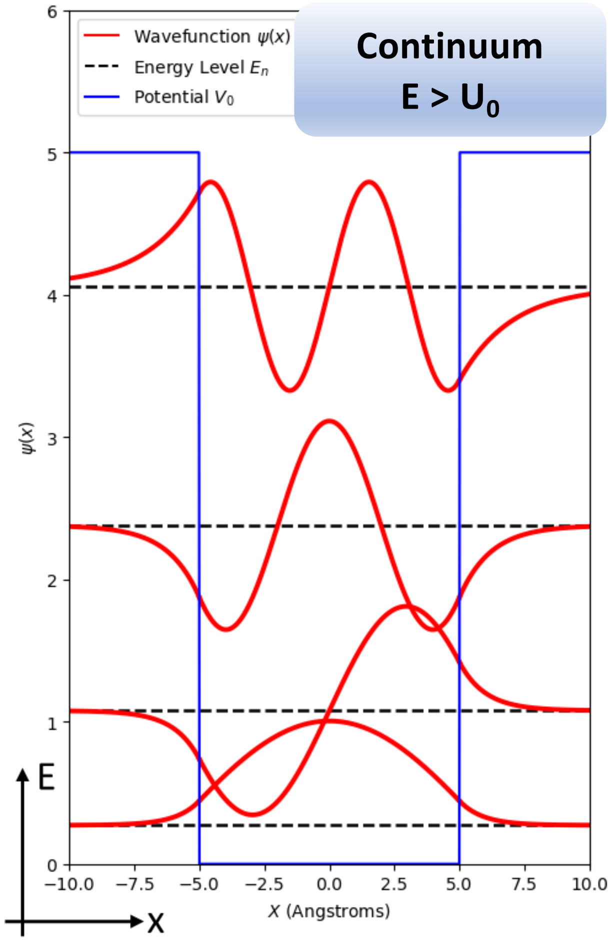
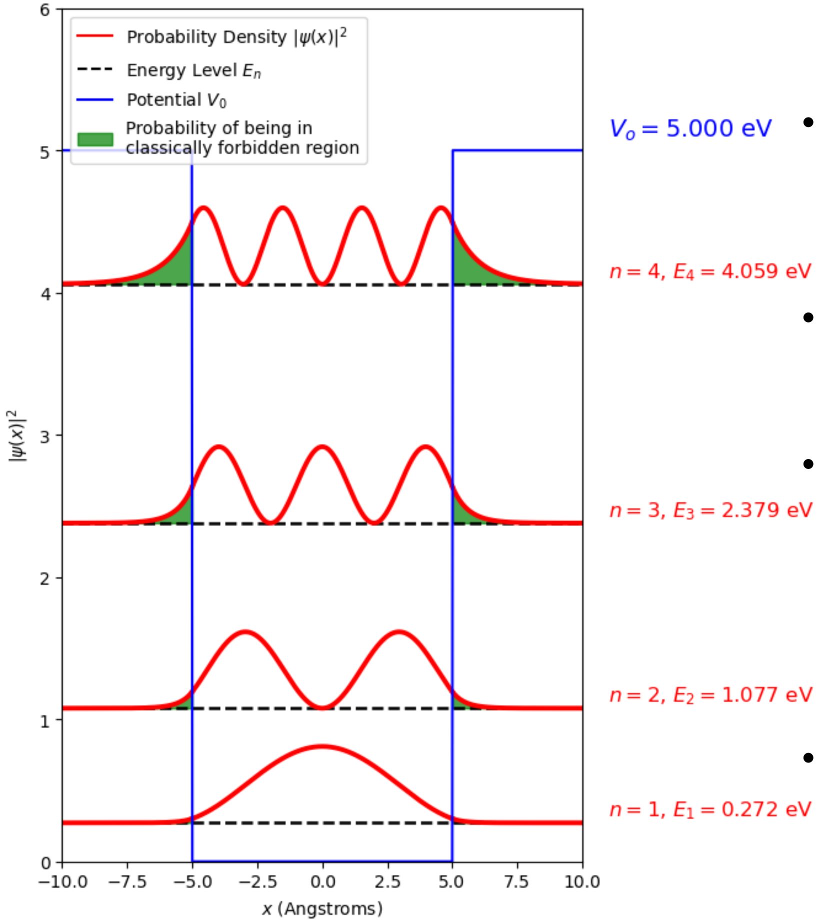
Visualizing wave function in finite potential well

L = 1 nm; m= m_e





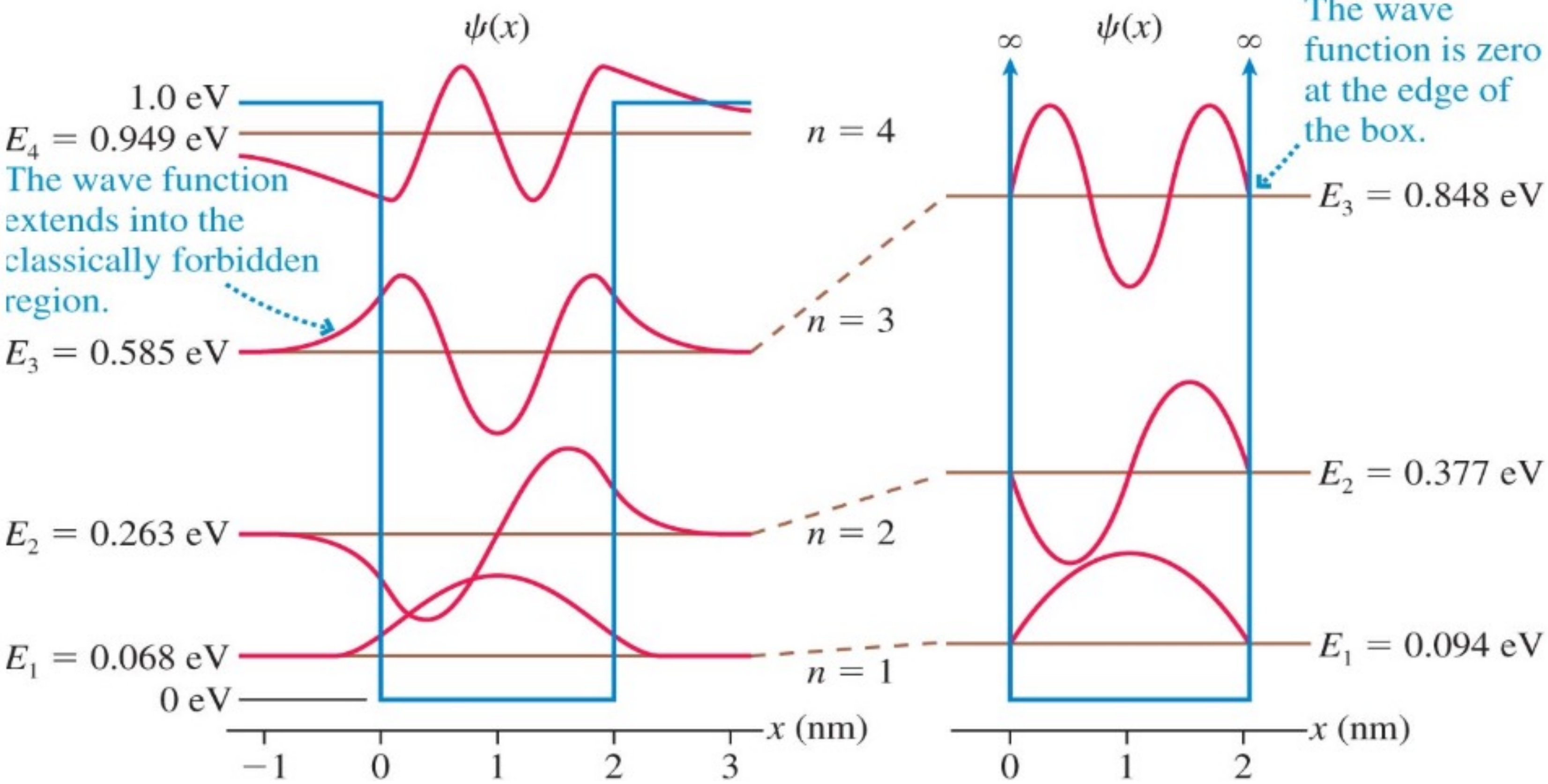
Important points to note:

- Unlike infinite well, only finite bound states are possible (4 in this case, E < U_0 5 eV)
- Bound states are also quantized. Free states are not (continuum).
- Deviation from classical mechanics: though E<U_0, there is a finite probability of particle existing ***'inside the wall'*** as if entering the wall.
- This probability dies down exponentially on either side of the wall

Comparison of finite and infinite potential wells

L = 2 nm; m= m_e

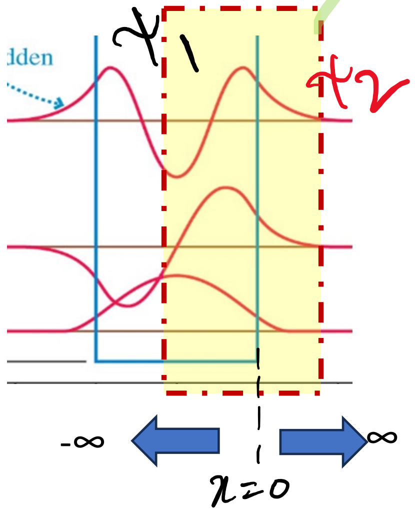
U_0 = 1 eV **U_0 = infinite**



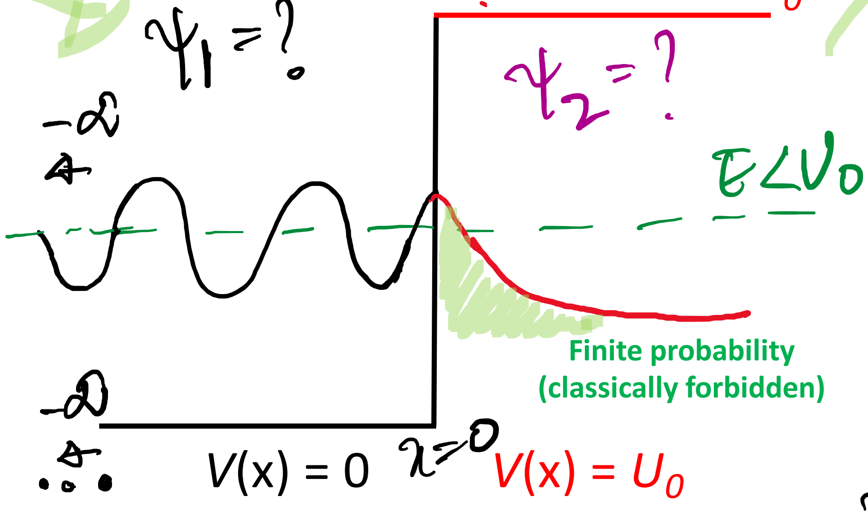
Think intuitively: Why E_n (Finite) < E_n (Infinite) for same mode '*n*' ? Difference grows with '*n*'

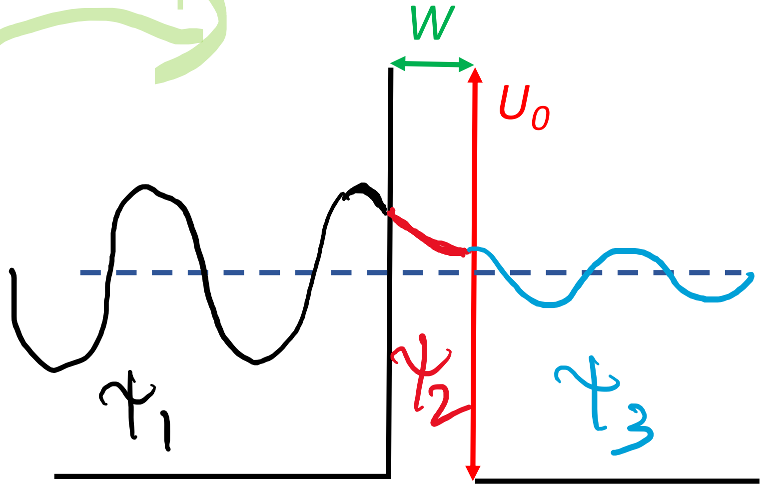
V(x)#3: From Well to Potential Barrier

Finite Well to barrier



w/o maths, Intuition





By only using intuitive reasoning, Can we write down for e- hitting a barrier? {for $E < V_0$}

ψ_1 @ $V(x) = 0 \Rightarrow x < 0$ {propagating}

ψ_2 @ $V(x) = V_0 \Rightarrow x > 0$ {evanescent/decaying}

$$\psi_1 = \underbrace{Ae^{ikx}}_{\text{Incident}} + \underbrace{Be^{-ikx}}_{\text{Reflected}} \quad \psi_r$$

ψ_i Incident {plane wave $+x$} Reflected. {plane wave $-x$}

$$\psi_2 = Ce^{-\alpha x}$$

Boundary Conditions?

$$\psi_1 = Ae^{ikx} + Be^{-ikx}$$

incident, reflected

$$\psi_2 = Ce^{-\alpha x}$$

$$\psi_3 = De^{ikx} + Fe^{-ikx}$$

transmitted

Transmission or TUNNELING BARRIER

NOTE:- ψ_1 & ψ_3 k, E same

Intensity/Probability reduced!

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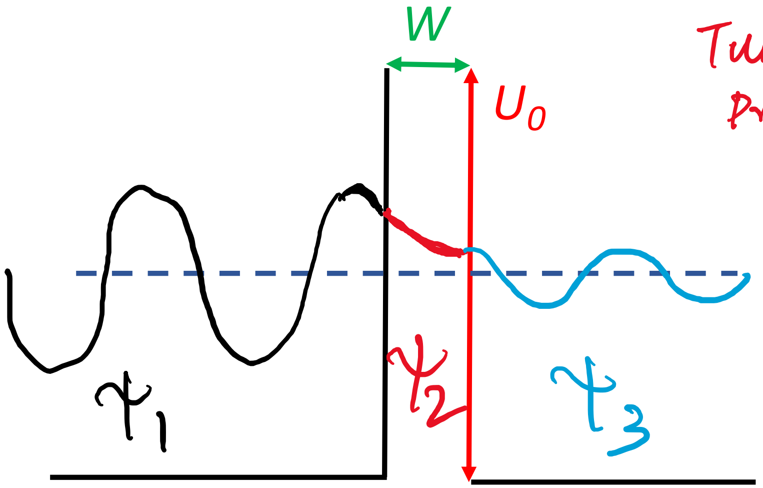
V(x) profile # 4: Tunneling through barrier



Transmission/Tunneling coeff/probability $T(E) = \dfrac{|\psi_{3,\,\text{transmitted}}|^2}{|\psi_{1,\,\text{incident}}|^2} = \left|\dfrac{D e^{ikx}}{A\, e^{ikx}}\right|^2$

$$T(E) \approx 16\,\frac{E}{U_0}\left(1-\frac{E}{U_0}\right)\exp(-2\beta W), \quad \text{where } \beta = \sqrt{\frac{2m}{\hbar^2}(U_0-E)}$$

$\{\text{for } E < U_0\}$

$\psi_1 = \underset{\uparrow\,\text{incident}}{A e^{ikx}} + \underset{\uparrow\,\text{reflected}}{B e^{-ikx}}$

$\psi_2 = C e^{-\alpha x}$

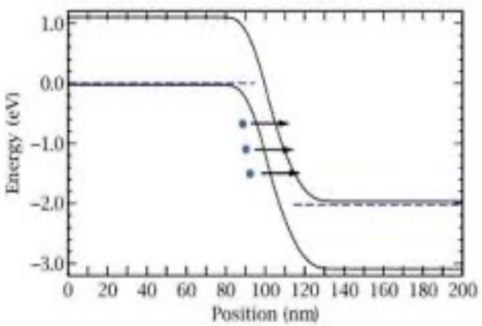
$\psi_3 = \underset{\uparrow\,\text{transmitted}}{D e^{ikx}} + F e^{-ikx}$ } Transmission or TUNNELING BARRIER

Intuition: Tunneling rate/probability

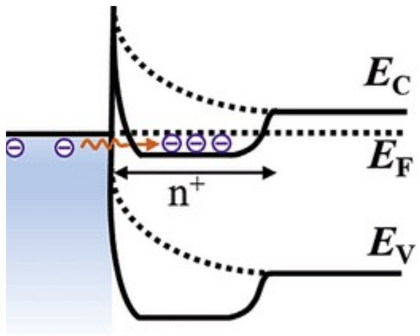
- reduce exponentially with barrier height and width (U_0 and W)
- Increases exponentially with E, of course for $E < U_0$

Importance: Nearly all semiconductor devices involve tunnelling.

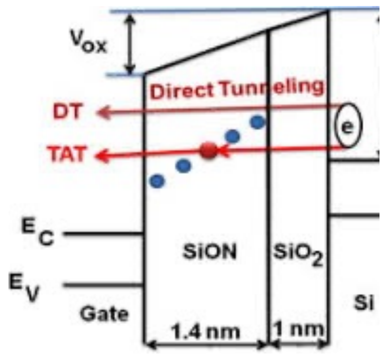
S/S Tunneling
Zener tunneling



MS Tunneling
Schottky contacts



MOS Tunneling
Gate leakage



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Summary- Quantum Mechanics

Behavior of electrons constrained by an electrostatic potential?

#1) Electrons can not be described by classical laws of particles / Waves SOLUTION :- Quantum mechanics!

#2) Q.M :- ψ {wave function} $\rightarrow$ Operators $\rightarrow$ $\underbrace{-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + V(x)\,\psi(x) = E\,\psi(x)}_{\text{SCRODINGERS' EQUATION (SCE)}}$

#3) SCE @ free space $\rightarrow \psi = A_\pm e^{\pm ikx}$; $E = \frac{\hbar^2 k^2}{2m}$; $P = \hbar K$; $K = 2\pi/\lambda$

#4) SCE @ particle in a infinite well + Boundary conditions.

- $\psi_n \rightarrow$ standing waves • $E_n = n^2 h^2 / 8mL^2 \rightarrow$ QUANTIZATION OF "ENERGY STATES"

#5) SCE @ finite well :- $\rightarrow$ Spreading of ψ_n into the WALLS.

#6) SCE @ V. thin barrier $\rightarrow$ Quantum mechanical TUNNELING $T(E) \propto e^{-(V_0-E)W}$