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ALL INDIA TEST SERIES CSE-2023

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4. **SUBJECT:-** Solid State and Electronics
5. **DATE:-** 09-07-2023

FOR OFFICE USE ONLY:-

Q.NO	MARKS
1.	$27\frac{1}{2}$
2.	32
3.	
4.	32
5.	32
6.	31
7.	
8.	

TOTAL MARKS	155/250

EXAMINER SIGNATURE

INVIGILATOR SIGNATURE

Q1(a)

Lattice constant is the dimension of the unit cell known as 'a'. It can be calculated using Debye - Schrerrer Method.

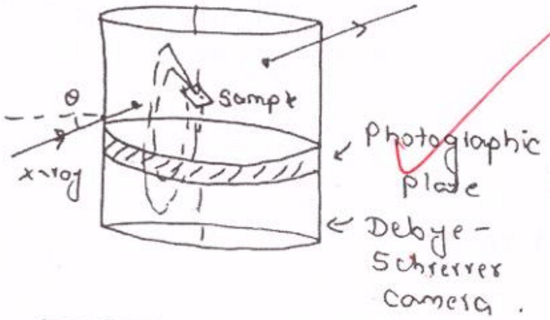


Fig 1. Debye Schrerrer setup

≡

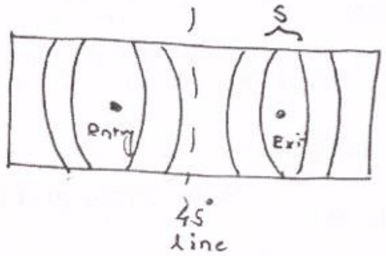


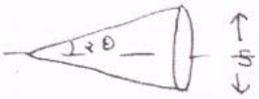
Fig 2. Photographic plate image

> We know from Bragg's diffiction,

$2d\sin\theta = n\lambda$. — ①

> Each θ forms a cone of diffraction which cut photographic plate in 2 planes.

> We know, $4\theta = S/R$



> We know, $d = \frac{a}{\sqrt{h^2+k^2+l^2}}$ } a = lattice parameter
h k l = miller indices.

$\Rightarrow$ In eq. ①, $2\frac{a}{\sqrt{h^2+k^2+l^2}}\sin\theta = n\lambda$.

Here we measure S → find θ. We know λ, we find 'a' for different values of {hkl} ⇒ Lattice constant obtained.

Other Methods

① Bragg's diffraction technique.

② Through density of solids if cubic structure (FCC, BCC, etc.) known

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Q1(b) Diffracted X-rays from crystal interfere only in specific direction giving Laue's pattern.

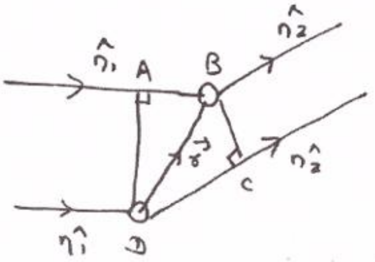

Fig 1. Diffraction from 2 atoms

> We know for constructive interference, $\frac{2\pi}{\lambda}\Delta = 2n\pi$

Here $\Delta = \vec{r}\cdot(\hat{n}_1 - \hat{n}_2)$

$= \vec{r}\cdot\hat{N}$. For a lattice, $\vec{r} = \vec{a}, \vec{b}$ or $\vec{c}$

$\Rightarrow \frac{2\pi}{\lambda}(\vec{a}\cdot\hat{N}) = 2n\pi$.

We know $|\vec{N}| = 2\sin\theta$. from fig 3.

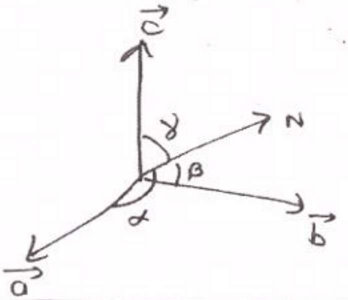

Fig 2. Normal $\hat{N}$

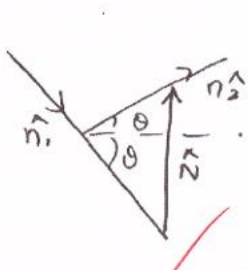

Fig 3. $\hat{n}_1 - \hat{n}_2$

$\Rightarrow \vec{a}\cdot\vec{N} = 2a\sin\theta\cos\alpha = h'\lambda = nh\lambda$.

Similiarly for other axes, we get,

$$\left.\begin{aligned} 2a\sin\theta\cos\alpha &= nh\lambda \\ 2b\sin\theta\cos\beta &= nk\lambda \\ 2c\sin\theta\cos\gamma &= nl\lambda \end{aligned}\right\}$$

Laue's equation where n = lcm of (hkl)

We know for any normal $\hat{N}$ at distance d, $d = \frac{a}{h}\cos\alpha = \frac{b}{k}\cos\beta = \frac{c}{l}\cos\gamma$

Substituting, $\boxed{2d\sin\theta = n\lambda}$.

Hence, Laue's equation is consistent with Bragg's law.

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Q1(c)

Bragg's law is the result of interference of diffracted x-rays from different atoms.

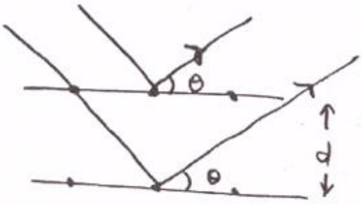

Fig 1. Bragg Diffraction

& states $2d\sin\theta = n\lambda$

Given $\lambda = 0.1512\,nm$,
$\theta = 20.2^\circ$.

$$\Rightarrow d = \frac{0.1512\times10^{-9}}{2\times\sin 20.2} = \boxed{0.219\,nm}$$

We know $d = \frac{a}{\sqrt{h^2+k^2+l^2}}$ $\Rightarrow a = d\sqrt{3}$ for (111) plane

$\Rightarrow$ $a = 0.38\,nm$; where a = lattice parameter

$$\text{Density}\ (\rho) = \frac{\frac{\#\text{atoms}}{\text{cell}}\times\frac{\text{Mass}}{\text{atom}}}{\text{Volume of cell}}$$ $\left\}\ \frac{\#\text{atoms}}{\text{cell}} = 4\right.$ for FCC.

$$\Rightarrow 2698 = \frac{4\times\frac{26.98\times10^{-3}}{N_a}}{a^3}$$ $\left\}\ N_a = \right.$ Avogadro number.

$\Rightarrow \boxed{N_a = \approx 7.2\times10^{23}}$ atoms / mol

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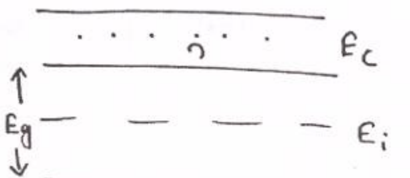
In actual, $N_a = 6.022\times10^{23}$ atoms / mol. Discrepancy due to difference in diffraction patterns.

Q1 (d).

Semiconductor is a solid-state device with band-gap between conductor & insulator. $\sim 1eV$



> Given $n = n_i(1+gx)$. As there is gradient in #electrons, it will lead to ~~dif~~ build-up of field.

Fig 1. Semi-conductor

> We know $\vec{J}$ = current density $= eD\frac{dn}{dx} \Rightarrow \vec{J} = eD\,n_i(g)$ } D = diffusion coeff.

Also $\vec{J} = \sigma\vec{E} = \mu(q)\,n\,(\vec{E})$

$\Rightarrow \cancel{e}D n_i(g) = \mu(e)\cancel{n}(\vec{E})$

$\Rightarrow \vec{E} = \frac{D}{\mu}\frac{(n_i g)}{n}$ } We know $\frac{D}{\mu} = \frac{kT}{q}$ } Einstein eq.

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$$\Rightarrow \boxed{\vec{E} = \left(\frac{kT}{q}\right)\frac{(n_i g)}{n}} = \boxed{\frac{kT}{q}\frac{(g)}{1+gx}}.$$

This electric field will lead to built-in potential in semi-conductor

Q1(c) Transistor is a 3-terminal device whose resistance can vary with voltage.

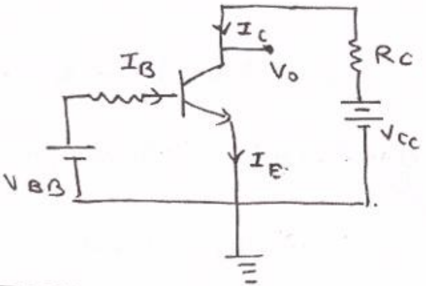

Fig 1. Transistor in CE configuration

Given: $I_C = 2.98$ mA, $I_E = 3$ mA, $I_{CO} = 0.01$ mA in CB.

We know,

$$I_C = \alpha I_E + I_{CO}$$

$$\Rightarrow \boxed{\alpha = 0.99} \checkmark$$

We know, $\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha} = \frac{0.99}{0.01} = 99$. ✓

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In CE mode, if $I_B = 30\,\mu A$, $I_C = 99 \times 30 = \boxed{2.97\,mA}$ ✗

$I_C = \beta I_B + (1+\beta) I_{CO} = 3.97$ mA

∴ Collector current in CE mode would be $\boxed{2.97\,mA}$ ✗

Transistors form the base of calculating algorithms, AI, ML today.

Q(2) (a)

Face-centred cubic is a type of close packed structure with 4 atoms per cell & packing fraction of ~74%. Eg:- Au, Ag, etc.

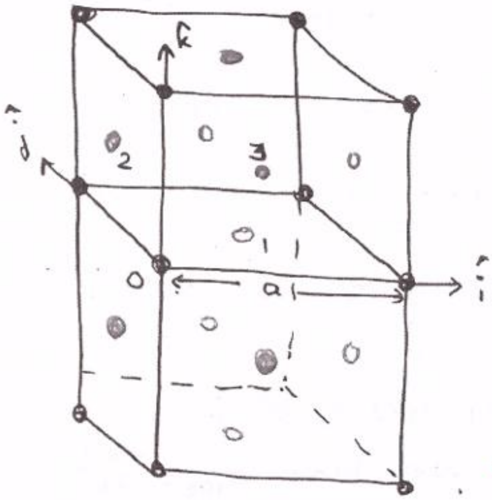

Fig 1. FCC structure

(i) Translation vectors $\vec{a}, \vec{b}, \vec{c}$ are vectors such that if cell is replicated along them, we get crystal itself.

Here assuming origin as shown, translation vectors for atoms 1, 2, 3 as marked are :-

$$\boxed{\vec{a} = \frac{a}{2}(\hat{i}+\hat{j}) \ ; \ \vec{b} = \frac{a}{2}(\hat{j}+\hat{k}) \ ; \ \vec{c} = \frac{a}{2}(\hat{k}+\hat{i})}$$

(ii) Volume of a parallelopiped bound by vectors $\vec{a}, \vec{b}, \vec{c}$ is given by

$$V = \vec{a}\cdot(\vec{b}\times\vec{c})$$

$$\Rightarrow \vec{b}\times\vec{c} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ 0 & 1 & 1 \\ 1 & 0 & 1 \end{vmatrix} = (\hat{i}+\hat{j}-\hat{k})\frac{a^2}{4}.$$

$$\Rightarrow \vec{a}\cdot(\hat{i}+\hat{j}-\hat{k})\frac{a^2}{4} = \frac{a^3}{8}(2) = \boxed{\frac{a^3}{4}}$$

where a = lattice parameter

(iii) Reciprocal vectors are the vectors in reciprocal lattice with magnitude inversely proportional to inter-planar distance of (hkl) & direction to normal to them.

$$\Rightarrow \sigma_{hkl} = \frac{1}{d_{hkl}}\hat{n}$$ For $hkl = 100$, we have $\sigma_{100} = \vec{a}^*$

$$\Rightarrow \vec{a}^* = \frac{1}{d_{100}}\hat{n} = \frac{\text{area}}{\text{Volume}} = \frac{\vec{b}\times\vec{c}}{\vec{a}\cdot(\vec{b}\times\vec{c})}$$

We know $\vec{a}\cdot\vec{a}^* = 2\pi \Rightarrow \vec{a}^* = 2\pi\dfrac{\vec{b}\times\vec{c}}{\vec{a}\cdot(\vec{b}\times\vec{c})}$

Similiarly, cyclic permutation gives,

$$\vec{a}^* = 2\pi\frac{(\vec{b}\times\vec{c})}{\vec{a}\cdot(\vec{b}\times\vec{c})}$$

$$\vec{b}^* = 2\pi\frac{(\vec{c}\times\vec{a})}{\vec{a}\cdot(\vec{b}\times\vec{c})}$$

$$\vec{c}^* = 2\pi\frac{(\vec{a}\times\vec{b})}{\vec{a}\cdot(\vec{b}\times\vec{c})}$$

Substituting values of $\vec{a}, \vec{b}, \vec{c}$ from (i),

$$\boxed{\begin{aligned} \vec{a}^* &= \frac{2\pi}{a}(\hat{i}+\hat{j}-\hat{k}) \\ \vec{b}^* &= \frac{2\pi}{a}(-\hat{i}+\hat{j}+\hat{k}) \\ \vec{c}^* &= \frac{2\pi}{a}(\hat{i}-\hat{j}+\hat{k}) \end{aligned}}$$

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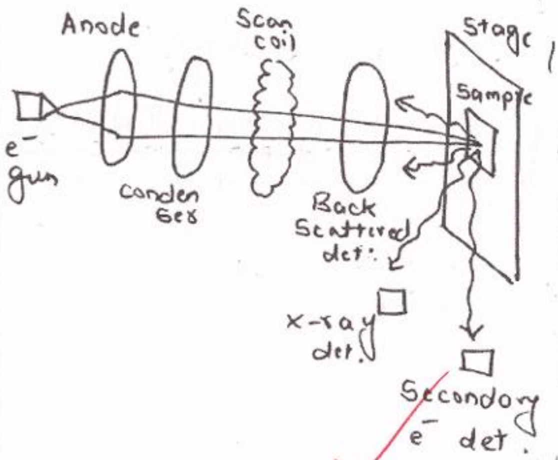
Reciprocal vectors are used to analyze Bragg's diffraction by constructing Brillouin Zones.

Q2(b). Microscopes help us zoom-in into the objects. As magnification is $\propto 1/\lambda$, using electrons, we get magnification ~ 1000x that of light. We have two types of electron microscopes.

Scanning Electron (SEM)

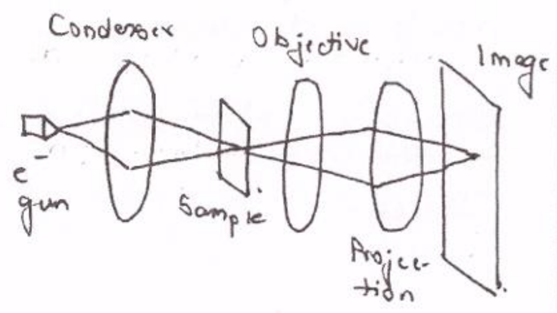


Working:- High energetic electrons scan the sample in Raster pattern giving

(i) Back-scattered e⁻: Change in KE measured

(ii) Secondary e⁻: Due to ionizations — provides morphology & topography.

Transmission Electron (TEM)



Working:- (i) e⁻ pass through the sample i.e 'transmit'

(ii) Shadow image is formed based on density / composition of sample.

(iii) e⁻ are projected using electro-magnetic

(iii) X-ray :- Due to e^- transition from L to K shells.

Application (i) Analyzing nano-meter structures.

Eg:- Carbon nanotubes

(ii) Understanding electrical conductivity, crystal structure of solids.

Limitations :- (i) Solid sample (ii) Pressure $<10^{-5}$ torr (iii) Size limited to 10×10×4cm.

lenses. Here e^- actually pass through sample v/s only scattering back in SEM.

Application :- (i) Analyzing structure of atomic scale objects.

Limitations :- (i) Extremely thin sample.

(ii) Transmission might damage sample.

Eg:- Biological tissues

$\frac{9\frac{1}{2}}{15}$

Recently, Pashmina Shawl Exporters Association asked custom officials to use SEM to identify original Pashmina Shawl from Shahtoosh shawl

Q.(2) (c)

Super-conductors are special material which show 0 electrical resistance & expel magnetic-field in them.

Characteristics of Superconductor.

① Different state of matter altogether.

② Shows 0 electrical resistance below critical temperature & critical field

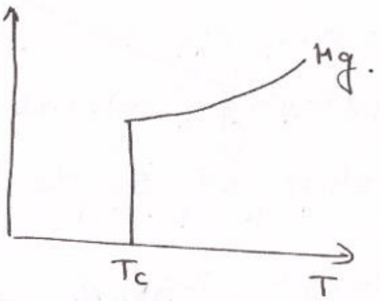


Fig 1. ρ v/s T for SC

③ Meissner effect:- Expels magnetic field inside it

④ Conduction due to Cooper pairs i.e. pair of electrons acting as Bosons.

⑤ Finite energy gap to excite elections from super-conducting stage to normal conduction stage

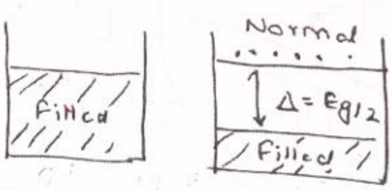


Fig 2. Conductor v/s SC

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London Equation Gives the penetiation depth i.e. finite distance till where magnetic field penetrates inside super-conductor.

We know, $m\frac{d\vec{v}}{dt} = e\vec{E} \Rightarrow \frac{d\vec{J}}{dt} = \frac{ne^2}{m}\vec{E}$ — ①

as $\vec{J} = ne\vec{v}$.

$$\Rightarrow \frac{d}{dt}(\vec{\nabla}\times\vec{J}) = \frac{ne^2}{m}(\vec{\nabla}\times\vec{E}) = -\frac{\partial \vec{B}}{\partial t}\left(\frac{ne^2}{m}\right)$$ } From Maxwell Eq.

$$\Rightarrow \vec{\nabla}\times\vec{J} = -\frac{ne^2}{m}\vec{B} \quad — ② = -\frac{ne^2}{m}\vec{\nabla}\times\vec{A}$$

$\therefore \vec{J} = -\frac{ne^2}{m}\vec{A} \longleftarrow$ ⓪

We know $\vec{\nabla}\times\vec{B} = \mu_0\vec{J}$ } From Maxwell eq.

$$\Rightarrow \vec{\nabla}\times\vec{\nabla}\times\vec{B} = -\nabla^2\vec{B} = \mu_0\vec{\nabla}\times\vec{J}$$

$$\Rightarrow \nabla^2\vec{B} = \frac{ne^2\mu_0}{m}\vec{B} \Rightarrow \nabla^2\vec{B} = \frac{1}{\lambda^2}\vec{B} \quad — ③$$

$$\Rightarrow \boxed{\vec{B} = B_0 e^{-x/\lambda}}$$ This is london equation

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where $\lambda = \sqrt{\frac{m}{ne^2\mu_0}} \approx \boxed{10^3 A^\circ}$.

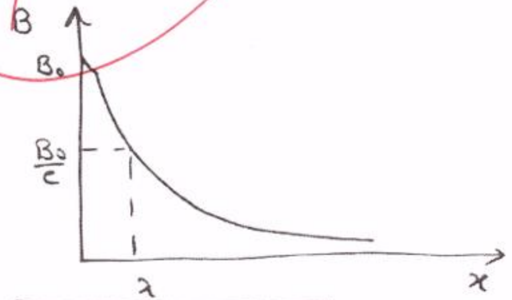

Fig 3. B v/s x

This shows that till ~ $10^3 A^\circ$, magnetic field penetrates inside the superconductor.

> This finite penetration ensures that super-current doesn't become infinite in superconductor

> For $x > \lambda$, $B \approx$ negligible $\Rightarrow$ Magnetic field expelled $\Rightarrow$ Superconductor shows Meissner effect.

Superconductors are used to sustain high currents in technologies such as maglev, nuclear fusion, etc.

Q4 (a)

Energy bands of solids give the allowed & forbidden energy levels thus classifying materials as conductors, semiconductors & insulators

> In reduced - zone scheme of plotting, all the energy levels are plotted into 1st Brillouin Zone

> This is done by using appropriate reciprocal lattice vector.

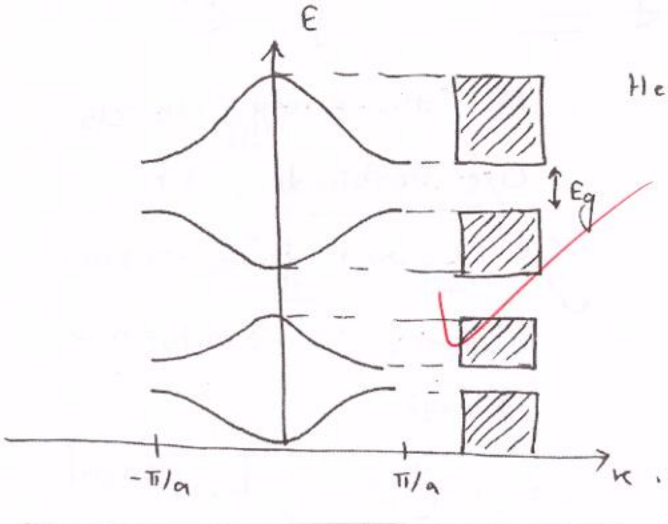

Fig1. Reduced Zone Scheme

Here, ▨ = Allowed bands

Eg = Band gap (Forbidden band)

> Both size of allowed & Forbidden increases with increasing E

Based on this, the materials can be categorized as :-

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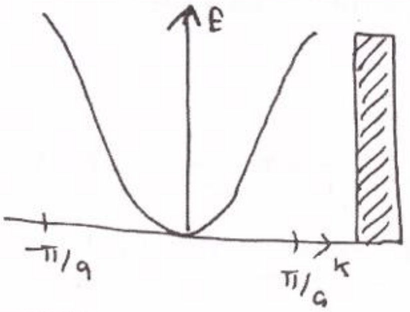
① **Conductors :-** $E_g \sim 0 eV \Rightarrow$ All the energy levels are allowed.

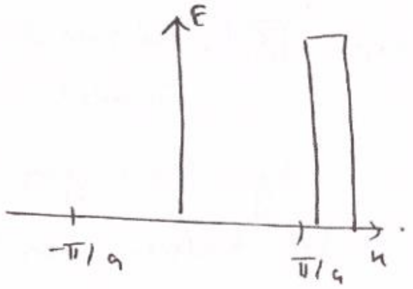


> The energy band is continuous i.e e^- can occupy all levels

$$\Rightarrow E = \frac{\hbar^2 k^2}{2m}.$$

Fig 2. E v/s k for conductor.

② **Insulators :-** $E_g > 6 eV$ ie. very large.



> All the energy levels are forbidden i.e. e^- cannot jump from valence to conduction band.

Fig 3. E v/s k for insulator.

> $E = \frac{n^2\pi^2\hbar^2}{2mL^2}$ } L = periodicity of lattice in metres.

③ **Semi-conductors :-** $E_g \sim 1 eV$.

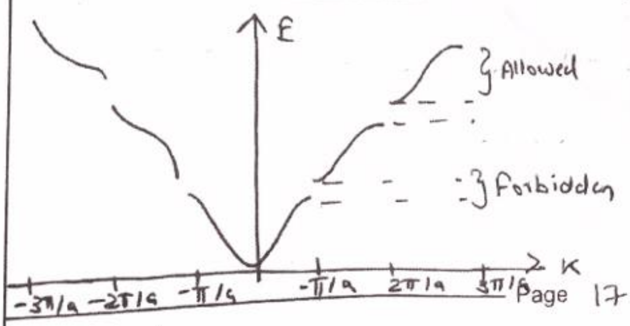


Fig ~~3~~4: E v/s k. For Semiconductors.

Here, some energy levels are allowed while some are forbidden.

> When appropriate energy (= allowed level), e^- jumps to conduction band & the material conducts.

This property makes it suitable to be used in computational circuits, digital circuits, etc. Typical intrinsic semiconductors are Si, Ge.

$\frac{12\frac{1}{2}}{20}$

Q4 (b)

Debye gave a model to calculate specific heat with assumptions as :-

① Molecules behave as Planck oscillator vibrating with different frequency forming discrete spectra $[\nu_1, \nu_2 \ldots \nu_m]$

② Total # modes = 3N.

③ Vibration are elastic waves i.e. have both transverse & longitudnal component.

$$\therefore dn = 4\pi V \left[\frac{2}{v_T^3} + \frac{1}{v_L^3}\right] \nu^2 d\nu \quad \Big\} \begin{array}{l} dn = \text{\# modes} \\ \text{in } d\nu + \nu \\ \text{to } \nu. \end{array}$$

Assuming $v_T \sim v_L \sim V_{mean}$,

$$dn = 4\pi V \left(\frac{3}{v_{mean}^3}\right) \nu^2 d\nu$$

$$\Rightarrow \int dn = 3N = 4\pi V \left(\frac{3}{V_{mean}^3}\right) \int_0^{\nu_m} \nu^2 d\nu$$

$$\Rightarrow V_{mean}^3 = (\nu_m^3) \left(\frac{4\pi V}{3N}\right)$$

$$\Rightarrow V_{mean} = (\nu_m) \left(\frac{4\pi V}{3N}\right)^{1/3}.$$

Considering one mole of atoms, $N = N_a$, $\rho = M/V$

$V_{mean} = \nu_m \left(\frac{4\pi M}{3N_a \rho}\right)^{1/3}$ } we know, θ_D = debye temp = $\frac{h\nu_m}{k}$

$\Rightarrow V_{mean} = \frac{k\theta_D}{h}\left(\frac{4\pi(12)}{3N_a(\rho)}\right)^{1/3}$

$\Rightarrow V_{mean} = \frac{k\theta_D}{h}\left(2.38\times10^{-29}\right)^{1/3} = \boxed{1.2\times10^{4}\ m/s}$

$>$ Dominant mode of lattice vibration = most prevalent mode $\lambda_d = \frac{\theta_D(a)}{T}$

Assuming T = 300k, a = 1.54 A°,

λ_d = 10.26 A°

$\Rightarrow \nu_d = \frac{V_{mean}}{\lambda_d} = \boxed{1.168\times10^{13}\ Hz}$.

∴ Mean velocity of sound is $\boxed{1.2\times10^{4}\ m/s}$ vibrating at dominant frequency of $\boxed{1.168\times10^{13}\ Hz}$.

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It is used to estimate debye temperature / density of materials

Q 4 (c)

Josephson junction is a thin strip of metal oxide (~10 A°) sandwiched between 2 identical super-conductors

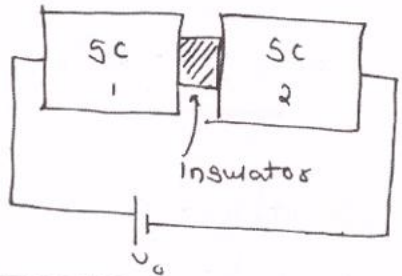

Fig 1. Josephson Junction

> We know, conduction in super-conductors is due to cooper-pair i.e. pair of electrons

⇒ For every cooper-pair transferred from SC-1 to SC-2, energy transferred = $2eV_o$.

> We know $E = h\nu \Rightarrow \nu = \frac{2eV_o}{h}$

$\therefore$ For $V_o = 0.5\,mV$, $\boxed{\nu = 2.42 \times 10^{11}\,Hz}$

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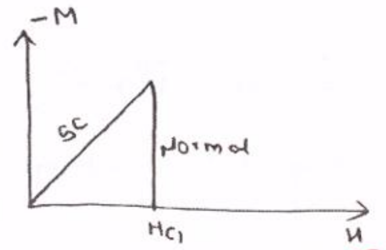
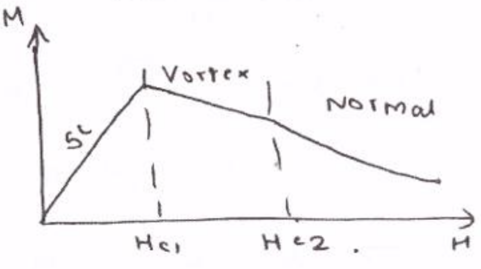
Josephson junctions are used to measure extremely low potential of the order ~ μV.

Q5 (a)

Type - I & Type - II are two types of semi-conductors based on the material.

	Type - I	Type - II
M v/s H (applied)		
Explanation.	> Very low critical field (~0.1 T for Pb) — Supercondue-tivity breaks easily.	> High critical field (~10T for Pb-Bi) → Higher resistance of super-conductivity.
Meissner	Perfect	Imperfect - presence of normal + superconducting stage (vortex)
Applications	Low	High in number
Examples	Pb	Pb-Bi, LBCO, etc.

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Superconductors can be used to produce ultra-efficient energy storage in future

Q5(b).

Magnetic susceptibility gives the ratio of Magnetization to applied magnetic field.

$\Rightarrow \chi = \frac{M}{H}$.

We know $\vec{B} = \mu\vec{H} = \mu_0(\vec{H}+\vec{M})$

where μ = permeability of material.

$\rightarrow \mu = \mu_0\left(1+\frac{\vec{M}}{\vec{H}}\right) = \mu_0(1+\chi)$

$\Rightarrow \boxed{\mu = 1.256\times10^{-6}\ H/m}$ ✓

$\mu_r = 1+\chi$
$= 1+9.48\times10^{-11}$
$\simeq 1$

$\frac{6\frac{1}{2}}{10}$

Relative permeability $= \frac{\mu}{\mu_0} \approx \boxed{1 = \mu_r}$ ✓.

$\mu = \mu_0\mu_r$
$= 4\pi\times10^{-7}[1+9.48\times10^{-11}]$
$= 4\pi\times10^{-7}$ SI

As the susceptibility is very small but (+ve), it is a paramagnetic material. Small value shows presence of weak ~~m~~ dipole moment.

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Q5 (c)

Saturation current is the current in p-n junction due to diffusion of minority carriers across the junctions.

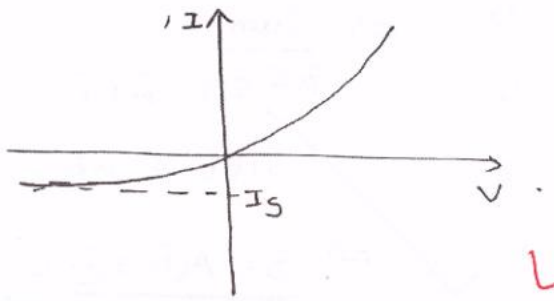


Fig 1. VI diode characteristics

We know for diode,

$I = I_S\left[e^{qV/\eta kT} - 1\right]$

where I_S = Saturation current density

For $I = 10^4\ A/m^2$

with $I_S = 200\,mA/m^2$,

$10^4 = 200 \times 10^{-3}\left[e^{qV/\eta kT} - 1\right]$

$\Rightarrow e^{qV/\eta kT} \simeq 50{,}000$ } Assuming $\eta = 1$,

$V = \frac{kT}{q} \ln 50{,}000 \Rightarrow \boxed{V = 0.28\ V}$

$6\frac{1}{2}$ / 10

As the inbuilt voltage of Ge = 0.3V,

total forward voltage = 0.28 + 0.3

$= \boxed{0.58\ V}$

In forward bias, current is majorly due to diffusion of carriers.

Q5 (d)

Circuit to add 3 bits A, B, C is known as Full- adder circuit. .

A	B	C	Sum	Carry.
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

$\Rightarrow$ Sum = $\bar{A}\bar{B}C + \bar{A}B\bar{C} + A\bar{B}\bar{C} + ABC$

$\Rightarrow S = A \oplus B \oplus C$.

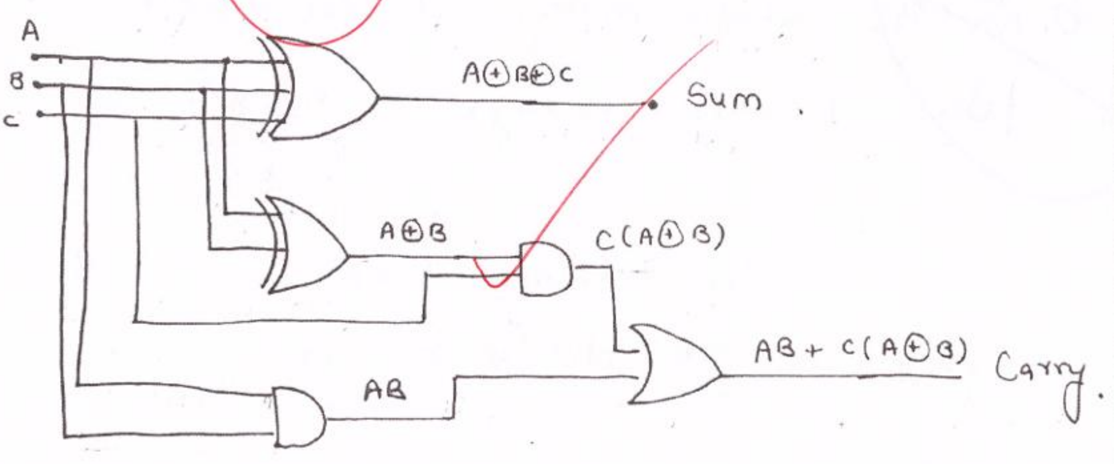
Carry: $\bar{A}BC + A\bar{B}C + AB\bar{C} + ABC$

$= AC(B+\bar{B}) + B(\bar{A}C + A\bar{C})$

$= AB + C(A \oplus B)$

6½/10

Circuit



Full-adder forms the basis of calculators today.

Q5 (c)

Karnaugh map technique provides Boolean expression simplification based on min terms, max terms.

A	B	C	$\bar{A}B$ +	$\bar{A}\bar{B}C$ +	$AB\bar{C}$ +	$A\bar{B}\bar{C}$	= Y
0	0	0	0	0	0	0	0
0	0	1	0	1	0	0	1
0	1	0	1	0	0	0	1
0	1	1	1	0	0	0	1
1	0	0	0	0	0	1	1
1	0	1	0	0	0	0	0
1	1	0	0	0	1	0	1
1	1	1	0	0	0	0	0

$\bar{A}B(C+\bar{C}) = \bar{A}BC + \bar{A}B\bar{C}$

Karnaugh Map

C \ AB	00	01	11	10
0	0	1	1	1
1	1	1	0	0

6½

Min terms = Σm_i = 1, 2, 3, 4, 6

Max terms = ΣM_i = 0, 5, 7.

$$\Rightarrow Y = \bar{A}B + A\bar{C} + \bar{A}C$$

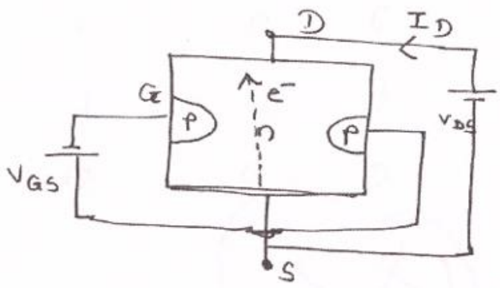
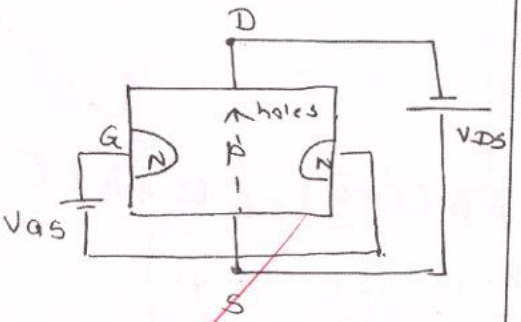
$$\Rightarrow \boxed{Y = \bar{A}B + (A \oplus C)}$$

Karnaugh map helps optimize the logic gates in circuit.

Q.6 (a)

Field Effect Transistor is called unipolar transistor because the conduction happens in it through only one-type of carriers i.e. either electrons or holes.

2 types of FET

n-Channel	p-Channel
	
> Channel is of n type semiconductor with gates of p-type.	> Channel of p-type substrate v/s gates. of n-type
> Conduction through electrons only	> Conduction through holes only
> $V_{GS} < 0$ $V_{DS} > 0$	$V_{GS} > 0$ $V_{DS} < 0$.

In Bipolar Junction Transistor (BJT), conduction is due to both - holes & electrons.

Superiority of FET v/s BJT

① High input impedance ⟹ Lower noise

② High power gain ⟹ No need of driver circuit.

③ Negative thermal coefficient ⟹ No risk of thermal runaway.

④ Higher operating speed, lower power consumption.

9/15

IC 2N547 is used as FET in digital electronics

Q6(b) Truth-tables are the outputs w.r.t. inputs which can be used to obtain Boolean expression

A	B	C	Y
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1

$\Rightarrow Y = \bar{A}\bar{B}C + \bar{A}B\bar{C} + A\bar{B}\bar{C} + ABC$

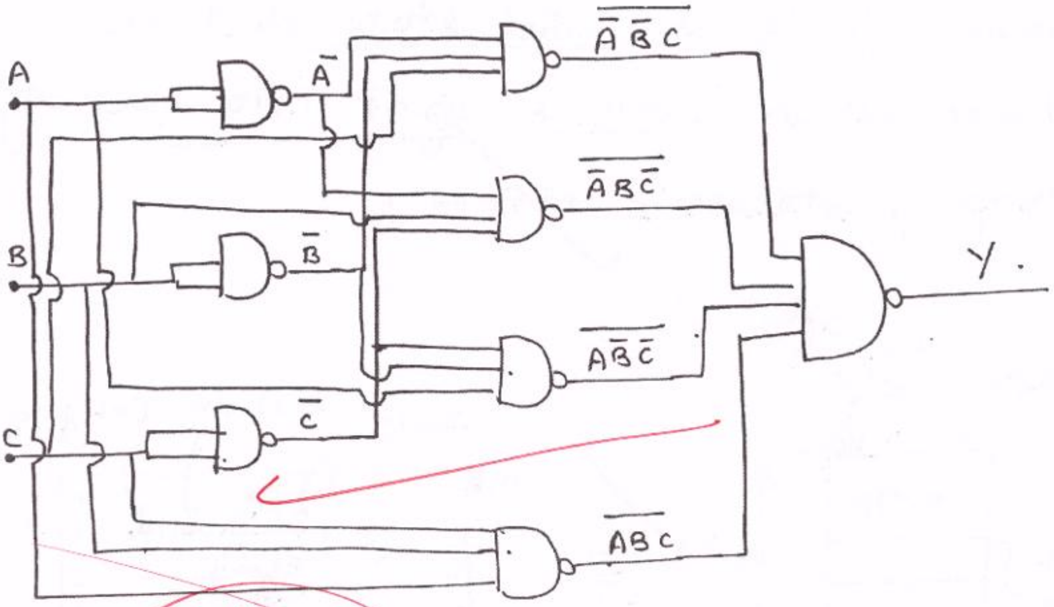
Any expression can be realised using NAND gates if it is in sum of product form.

From De-morgan law, we know, $\bar{A}+\bar{B}+\bar{C} = \overline{ABC}$.

$$\Rightarrow Y = \bar{A}\bar{B}C + \bar{A}B\bar{C} + A\bar{B}\bar{C} + ABC$$

$$= \overline{(\overline{\bar{A}\bar{B}C})(\overline{\bar{A}B\bar{C}})(\overline{A\bar{B}\bar{C}})(\overline{ABC})}$$

This can be realized using NAND gates as:-

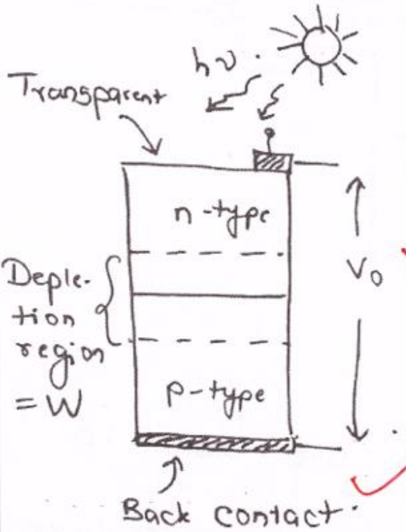


$\frac{9+}{15}$

Logic circuits are used in Arithmetic Logic Unit of microprocessors.

Q6
(c)

Solar cell is a solid state electronic device which converts light into electricity using photovoltaic effect.



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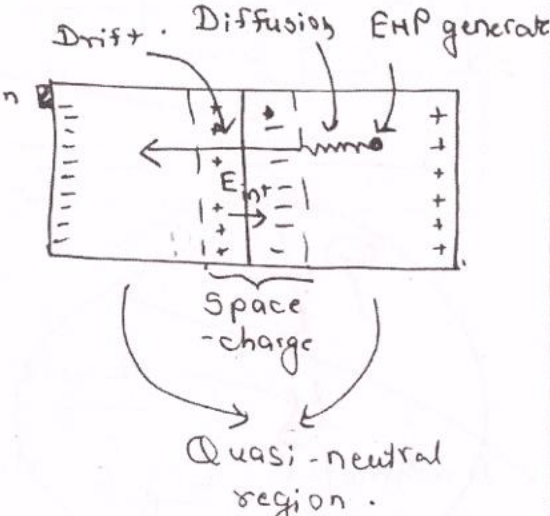

Fig1. Solar-cell circuit

Fig 2. Working of solar cell

Working

> When light falls on solar cell, Electron Hole Pair (EHP) is generated in both space charge & quasi neutral region,

> Initially e^- diffuse towards depletion region & then are swept by internal field in Depletion region to n-side

> Similiarly, holes generated in n-side are swept to p-side.

⇒ All e^- accumulate on n-side, all holes on p-side ⇒ potential created.

Let # EHP generated = $G = G_0 e^{-\alpha x}$ where G_0 = generation at surface, α = absorption coefficient.

$$\Rightarrow \frac{dn}{dt} = G(A\,dx) \Rightarrow \frac{dn}{dt} = \int_0^L G_0 A e^{-\alpha x}\,dx$$

where $L = L_e + L_h + W$ = electron diffusion length + hole diffusion length + depletion width

$$\Rightarrow \frac{dn}{dt} = AG_0 \left[\frac{e^{-\alpha x}}{\alpha}\right]_L^0$$ } Assuming α to be large.

$$\frac{dn}{dt} = AG_0\left[L_e + L_h + W\right] \Rightarrow I = \frac{q\,dn}{dt}$$

$\therefore \boxed{I_{ph} = eAG_0\left[L_e + L_h + W\right]}$ This is current produced due to photovoltaic action

But solar-cell is a pn junction diode

$\Rightarrow I_{diode} = I_d = I_s\left[e^{qV/nkT}-1\right]$

$\Rightarrow I_{total} = I_d - I_{ph} = \boxed{I_s\left[e^{qV/nkT}-1\right] - I_{ph}}$

Now if,

① Circuit is shorted:- $V = 0 \Rightarrow I_{sc} = -I_{ph}$.

② Circuit is open: $I = 0 \Rightarrow V_{oc} = \frac{nkT}{q}\ln\left[\frac{I_{ph}}{I_s}+1\right]$

where I_s = reverse saturation current.

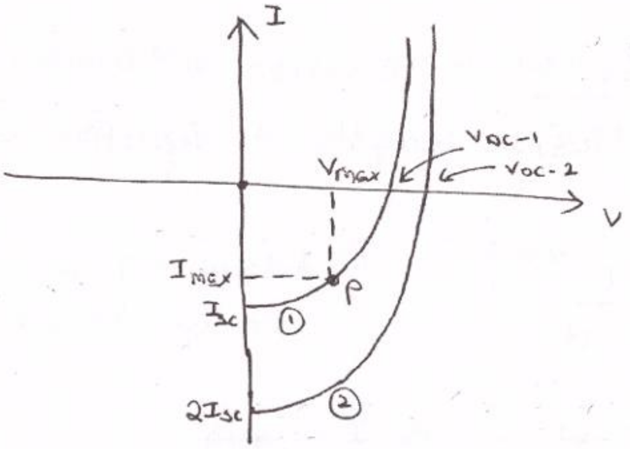

Fig 3:- VI characteristic of solar cell.

> 2 cases - in case 2, incident light intensity = 2 (case-1) $\Rightarrow I_{sc}$ doubles but V_{oc} remains ~ same.

However, V_{oc}, I_{sc} cannot be realized together $\Rightarrow P_{max}$ = optimal point for maximum power output = $V_{max} I_{max}$

Fill factor (FF) = $\frac{V_{max} I_{max}}{V_{oc} I_{sc}}$

$\Rightarrow \eta$ = efficiency = $\frac{V_{oc} I_{sc} (FF)}{\text{Incident intensity}}$.

Solar energy will form the bulk of contribution in India's 2070 goal of 50%. energy from renewables.

12½/20

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