

1. What are photoresists (PR)? What are 3 primary components of PR? Describe 4 essential differences between positive and negative resist (Ans: Slide 11-13, Lithography 2)

Marks: 1+1.5+4=6.5

Photoresists:

Photoresists are polymers that are sensitive to light, and other higher energy sources of radiation such as electron beams and X-rays.

3 primary components of PR:

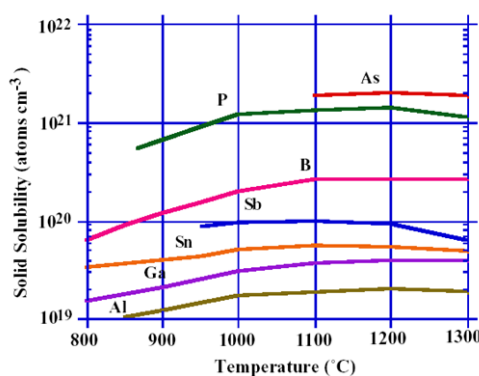
1. Binder
2. Sensitizer
3. Solvent

Typical Differences between positive and negative PR:

S.No.	Positive Photoresist	Negative Photoresist
1.	A <i>positive photoresist</i> is a type of photoresist in which the portion of the photoresist that is exposed to light becomes soluble to the photoresist developer. The unexposed portion of the photoresist remains insoluble to the photoresist developer.	A negative photoresist is a type of photoresist in which the portion of the photoresist that is exposed to light becomes insoluble to the photoresist developer. The unexposed portion of the photoresist is dissolved by the photoresist developer
2.	Minimum feature size obtainable: 0.5 μm	Minimum feature size obtainable: 2 μm
3.	Developer Base: Aqueous	Developer Base: Organic
4.	Relative cost: More expensive	Less expensive
5.	Adhesion to Silicon: Fair	Excellent
6.	Step coverage: Better	Lower
7.	Wet chemical resistance: Fair	Excellent

2. Equilibrium solid solubility curves for various dopants in silicon are given below. Write down at least two important inferences one can draw from this figure. What is meant by solid solubility? Why is electrical solubility limit found to be considerably lower than the maximum solid solubility shown in figure and what may happen to the excess dopants? Take the example of **Arsenic (As)**; Figure below suggests that As might be active up to the concentration of $2 \times 10^{21} \text{cm}^{-3}$, however in practice, it is difficult to achieve electrically active As concentration above $2 \times 10^{20} \text{cm}^{-3}$. Explain the origin of this discrepancy. Describe at least 2 advantages (for each type) and 2 disadvantages (for each type) of **“Ion implantation and Solid/Gas phase”** doping methods.

Marks: 2+1+2+3+4=11



Ans: section 7.2.1 (page: 375)

Inferences from the graph:

1. Figure shows the solid solubility curves for various dopants in Silicon. These values are the equilibrium solubilities at each temperature and may not be achieved in device doped regions. i.e. dopants exhibit retrograde solid solubility, where the maximum concentration that can be dissolved occurs below the melting point.
2. For concentrations higher than the solubility limit, the surplus impurity atoms would tend to precipitate and precipitates of As, P, or B, while possibly introducing the defect levels in the band gap, are not active as dopants.
3. The graph explains us that the solubility is rather large (with a maximum between 1200°C and 1400 °C). The real importance of the solid solubility curves thus in specifying how much doping can be achieved on top of the initial doping by e.g. diffusion or ion implantation.

Solid solubility:

The maximum concentration of a dopant that can be dissolved in Silicon under equilibrium conditions, without the formation of separate phases.

Why is electrical solubility limit found to be considerably lower than the maximum solid solubility shown in figure and what may happen to the excess dopants?

- Because of the neutral cluster formation with point defects in the silicon lattice, the electrical solubility limit may be considerably lower than the maximum solid solubility.
- Typically excess dopants i.e. dopants above electrical solubility limit form an inactive complex which is electrically neutral and do not contribute free carriers to the doped region.

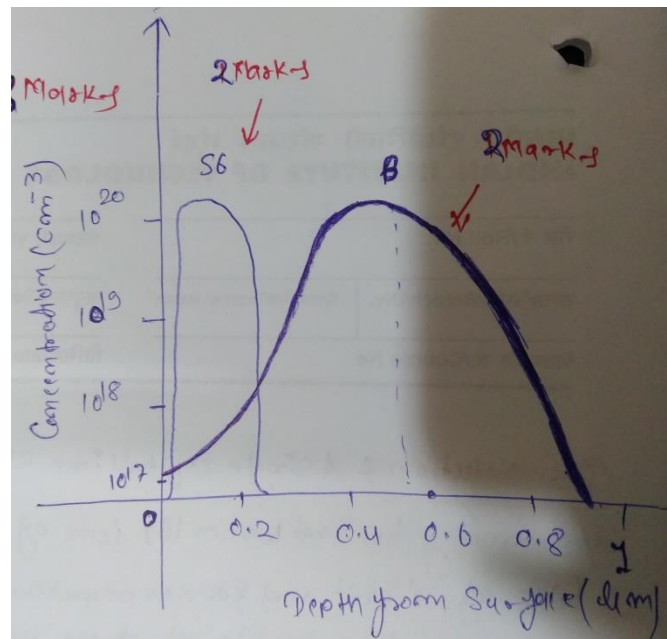
Origin of discrepancy in Arsenic doping limit:

- Laser melting of Silicon can introduce As into Silicon in metastable electrically active concentrations near the solubility limit.
- There is an enormous driving force which tends to inactivate the arsenic during any subsequent thermal cycling. Upon annealing, some of the arsenic, while not strictly forming a separate precipitate phase, forms an electrically inactive structure.

Advantages and Disadvantages of Ion implantation and Solid/Gas phase diffusion:

Advantages	
Ion Implantation and Annealing	Solid-/Gas-Phase Diffusion
Room temperature mask	No damage created by doping
Precise dose control	Batch fabrication
$10^{11} - 10^{16}$ atoms cm^{-2} doses	
Accurate depth control	
Disadvantages	
Ion Implantation and Annealing	Solid-/Gas-Phase Diffusion
Implant damage enhances diffusion	Usually limited to solid solubility
Dislocations caused by damage may cause junction leakage	Low surface concentration hard to achieve without a long drive-in
Implant channeling may affect profile	Low dose predepos very difficult

Q.3 Solution:-



{2-Marks}

Reason

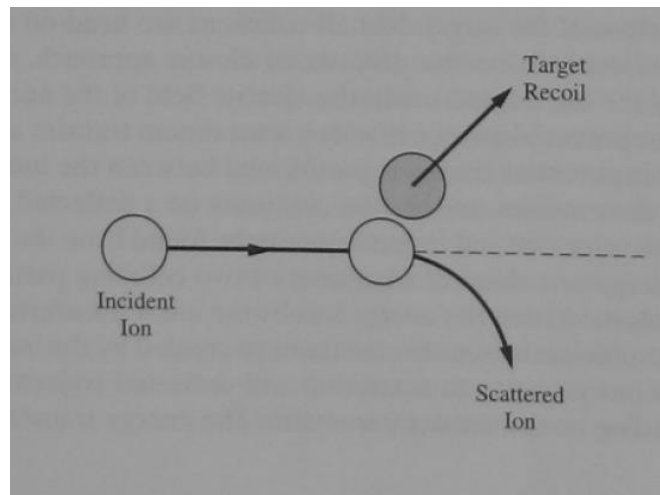
1. Antimony (Sb) is a heavy atom, so it can not go much inside in substrate in comparison to lighter atom-like Boron (B). **{1 Marks}**
2. At the same dose and energy, lighter atom goes more in-depth, so its profile becomes broader than heavier atom. **{1 Marks}**

Role of crystal structure {3 Marks}

1. With rotation and tilt of the crystal structure of silicon, it may behave like Amorphous silicon and help in minimizing the possibility of channeling for ions.
2. Due to some channeling effect, secondary peak occurs in profile.

Nuclear Stopping Power {2 Marks}

It is the elastic collision between the projection ion and atom in the sample. So the ions get scattered or deflected from their path. So ions losses their kinetic energy to the electric field due to atom. This loss of kinetic energy converts to the potential energy of the system, it leads to a reduction of ions energy, and they come to rest; this process is term as Nuclear stopping. **{1.5 Marks}**



{0.5Marks}

Type of defect created by the implemented ions in the substrate.{2 Marks, Any three defects}

- 1.Knocking off substrate atom from lattice structure.
- 2.Small defect clusters.
- 3.Dopant defect complex.
4. Interstitials and vacancies.

Process {2 Marks}.

- 1.Annealing at low temperature (400 degrees) results in breaking of vacancies complex (di-vacancies and vacancy type clusters), and these are annihilate with interstitials.
- 2.Annealing at high temperature (900 degrees) results in the evaporation of silicon interstitials from the ends of defects, results in reduction of defects.

Q7 → what are two main types of species involved in plasma etching process and briefly explain their role in the etching process. Give an example where both of these species are used to improve the etching of a semiconductor layer. Mark → $(0.5 + 2) \times 2 + 2.5 = 7.5$

Solution : Two main species involved in plasma etching process

1) Reactive Neutral Chemical Species ~~0.5~~ 0.5

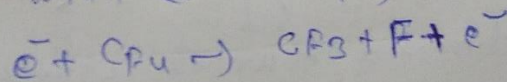
2) ions

→ 0.5

Role

Any two - 2 Marks →

1) Reactive Neutral Chemical Species are responsible for chemical etching. CF_3 , F are free radical generated by reaction with electron (e^-)



2) Ions for etching material so like Si , F react with Si and make SiF_4 (gas) byproduct and it is easily vaporized and expose more silicon to be etched.

- b) Isotropic etching of surface due to isotropic arrival Page-2
angle to surface and low sticking co-efficient when
chemical species act independently on surface.
- c) Good Selectivity of etchant material.

2) IONS (Any two - 2 marks)

- a) Due to creation of electric field, ions (Ar^+) will
etch the surface (sputtering like process) in the physical
etching process.
- b) When ions strike the surface once it does not
strike surface anywhere. So more ~~isotropic~~ anisotropic
behavior.
- c) It enhances the surface adsorption, etching
reaction and formation of Byproduct and removal
of by product from reacted etchant.

Example Chemical + Physical etching process (1.5 mark)

→ Ion-Enhanced Etching = chemical + physical etching process
Etching of Silicon by XeF_2 gas and Ar^+ ions.

- i) In process chamber XeF_2 gas (not a plasma, no physical
etching) is introduced. ~~the~~ Very little etching occurs (Part A of Graph)
- ii) Now Ar^+ ion beam is directed towards surface. So the
etch rate increase ten times (Part B of Graph). ~~Now~~
- iii) Now the XeF_2 gas is turned off. So now the etch rate
is almost zero (Part C of Graph)

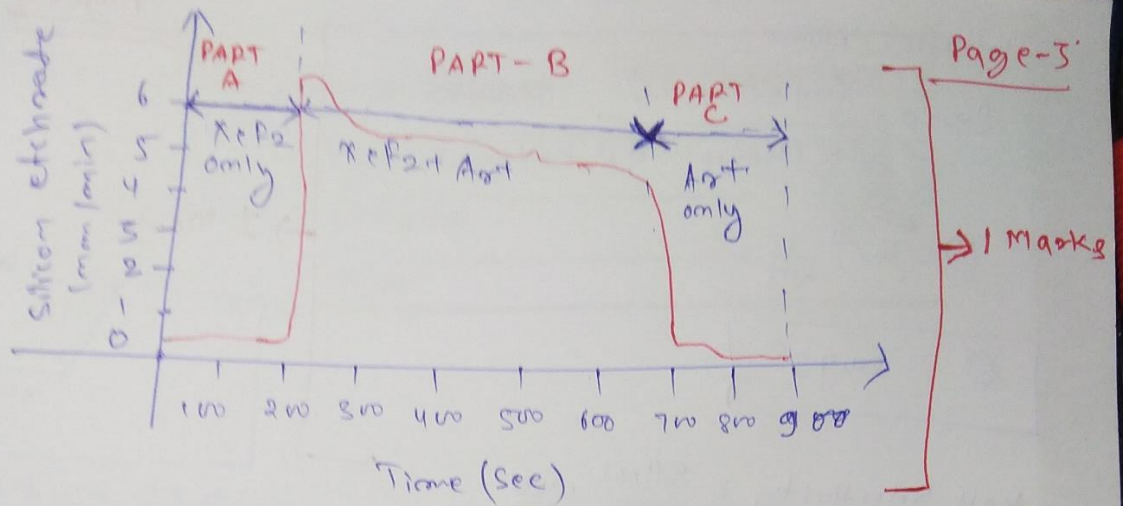


Fig - Etch rate vs time

Q8. Si (100) wafer shown below is exposed to KOH. Draw and briefly explain the profile of the etched layer. What is "etch stop" layer? Give example of at least three etch stop layers - $(2+1)+1.5+1.5 = 7$

Solution:

Solution:

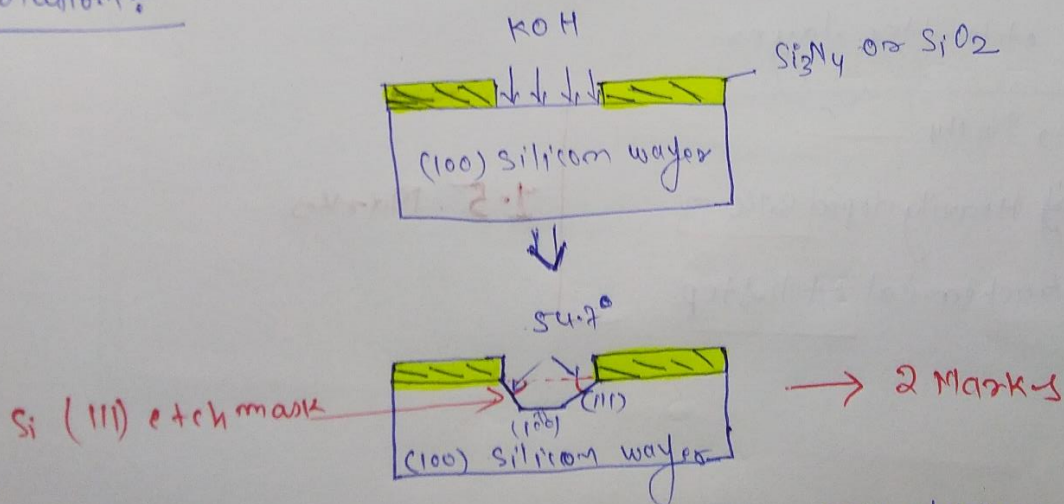


Fig:- Etch Profile after KOH etching.

Explanation

When KOH start etching the Si(100) plane etch faster as KOH etch deeper then (111) plane of Si exposed. So the etch rate changes and they give the same angle

with (100) plane

$$\cos \theta = \frac{(1 \cdot 1 + 0 \cdot 1 + 0 \cdot 1)}{\sqrt{1^2 + 0^2 + 0^2} \sqrt{1^2 + 1^2 + 1^2}}$$

$$\theta = \cos^{-1} \frac{1}{\sqrt{3}}$$

$$\theta = 54.73^\circ$$

$$\Rightarrow \text{KOH Selectivity} = \frac{\text{Si(100)}}{\text{Si(111)}} = \frac{100}{1}$$

\Rightarrow Density of $\langle 111 \rangle \gg \langle 110 \rangle, \langle 100 \rangle$

Etch Stop Layer $\frac{A}{a}$

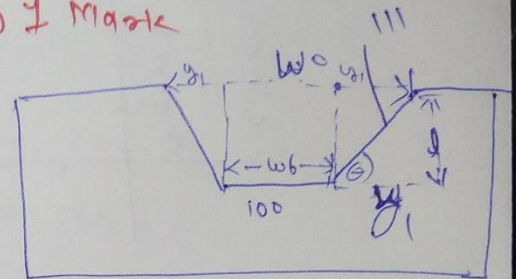
In etching process to control the etch depth specially in wet etching process, a layer is needed to stop the process is termed as Etch Stop layer

Different etch stop layers

- 1) $\text{SiO}_2, \text{Si}_3\text{N}_4$
- 2) Heavily Heavily doped Silicon
- 3) Electrochemical etch stop

Page-4

\rightarrow 1 Mask



$$w_o = 2y_1 + w_b$$

$$= 2d \tan \theta + w_b$$

$$w_b = w_o - 2d \tan \theta$$

$$= w_o - 2 \cdot d \cdot \tan 54.73^\circ$$

$$w_b = w_o - \sqrt{2} d$$

\rightarrow 1.5 Masks

1.5 Masks

Q4. Describe 2 advantages and 2 disadvantages of CVD and PVD techniques. (Ans: Lecture 23, slides) Name 3 different types CVD processes and give 2 essential characteristics of each of these processes. (Ans: Section: 9.2.1) What is boundary layer and why is it formed in CVD reactor? How does it affect the deposition of the thin film in horizontal type CVD reactor? (Ans: Page 519-522)

Marks:4+(1.5+3)+2+3=13.5

Sol.

Advantages of CVD

(0.5+0.5)

- Uniform distribution over large areas
- No compositional gradients across substrate
- Good surface coverage
- No need to break vacuum for source changes
- More selective area deposition because of higher activation energy for reaction with foreign substances.
- Isotropic deposition

Disadvantages of CVD

(0.5+0.5)

- Mostly involve safety and contamination
- Hydrides and carbonyls are poisonous (especially arsine)
- Metalorganics are pyrophoric (ignite in contact with air)
- High cost for compounds with sufficient purity

Advantages of PVD

(0.5+0.5)

- Do not involve safety and contamination issues
- Large no. of materials can be deposited
- Physical processes involve in the deposition
- Low deposition temperature
- Dense & Adherent coatings
- Atomic level control of chemical composition

Disadvantages of PVD

(0.5+0.5)

- Non Uniform Deposition
- Shadowing by surface topography
- Very poor surface coverage
- Highly directional
- Very little rearrangements of atoms usually occurs
- Low coating rates

3 Types of CVD processes and essential characteristics (Any 3 from below)

1. Atmospheric pressure CVD (APCVD) (0.5)+ (0.5+0.5)
 - a. CVD at atmospheric pressure.
 - b. Works in Mass transfer limited regime
 - c. To achieve uniform deposition the wafers are kept side by side so that the equal fluxes of reactant gases reach on every location
 - d. High deposition rates
 - e. Poor uniformity, purity is less than LPCVD
 - f. Used mainly for thick oxides.
2. Low-pressure CVD (LPCVD, at ~0.2 to 20 torr) (0.5)+ (0.5+0.5)
 - a. CVD at sub-atmospheric pressures.
 - b. Works in surface reaction limited regime
 - c. Excellent Uniformity, purity
 - d. Wafers are stacked vertically upright
 - e. Lower (but reasonable) deposition rates than APCVD
 - f. Used for polysilicon deposition, dielectric layer deposition, and doped dielectric deposition.
3. Plasma Enhanced CVD (PECVD) (0.5)+ (0.5+0.5)
 - a. Plasmas are used to force reactions that would not be possible at low temperature.
 - b. Uses low temperatures necessary for back end processing.
 - c. Plasma damage typically results.
 - d. Used for dielectrics coatings.
4. Metal Organic CVD (MOCVD) (0.5)+ (0.5+0.5)
 - a. Highly flexible—> can deposit semiconductors, metals, dielectrics
 - b. HIGHLY TOXIC!, Very expensive source material. Environmental disposal costs are high.
 - c. Dominates low cost optical (but not electronic) III-V technology, some metalization processes (W plugs and Cu)

Boundary Layer: For some distance, away from the wafer surface, the gas is not moving at all. The boundary that covers this region where gases doesn't move is known as Boundary Layer. Beyond the boundary layer the gas is well mixed and moving at a constant velocity parallel to the substrate surface. (1)

The boundary layer is caused by the frictional force of the gas stream on the stationary susceptor and wafers. If the gas velocity right next to the wafer surface were not zero, an infinitely large frictional force would exist right at the surface which would bring the velocity to zero there.

(1)

$$\delta_s(x) = \left(\frac{\mu x}{\rho U} \right)^{1/2} \text{-----} \quad (1) \quad (0.5)$$

ρ =gas density, μ =gas viscosity, U =velocity, x =distance along the susceptor.

$$h_G = \frac{D_G}{\delta_s} \text{-----} \quad (2) \quad (0.5)$$

h_G = Mass Transfer Coefficient ($cm \ sec^{-1}$), D_G =Diffusion coefficient of the reactant species across the boundary layer

As x increases, δ_s increases along the length of the susceptor(from equation (1)), (0.5)

then the effective mass transfer coefficient, h_G , decreases along the length of the susceptor(from equation (2)). (0.5)

The deposition of the thin film in horizontal type CVD reactor is limited by the mass transfer through the boundary layer, therefore, the deposition rate would decrease going from the front of the susceptor to the back. (1)

ENDSEM SOLUTION

5. Explain why DC sputter is not suitable for the deposition of insulator? How is this problem circumvented in RF sputter deposition system? What is reactive sputter deposition? Give an example (material) where reactive sputter deposition is used.

Marks: 2+2+2+1=7

Ans:

Since the target acts as an electrode in DC sputter deposition, target and the source material must be conductive in nature. Thus Al, W, Ti or other metals can be sputtered but this technique is not suitable for insulator deposition. With a negative DC voltage applied, positive argon ions from the plasma strike the negatively charged insulator and positive charge would accumulate. The negative surface voltage would become less than that required to sustain the glow discharge, and the plasma would shut down.

[Only stating the cause, 1 mark. With explanation, another 1 mark]

RF voltages can be coupled capacitively through the insulating target to the plasma, so that conducting electrodes are not necessary, and the positive charge buildup is neutralized by electron bombardment over each cycle. The RF frequency is chosen to be high enough so that a continuous plasma discharge is maintained, that is, higher than the effective RC time constant of the system. The difference in mass and hence mobility between the electrons and ions allows for virtually continuous sputtering of the target throughout both half cycles of the RF voltage.

[Only stating the event, 1 mark. With explanation, another 1 mark]

In the reactive sputter deposition, a reactive gas is introduced into the sputtering chamber. In addition to the Ar plasma, and the compound is formed by the elements of that gas combining with the sputtered material. For example, TiN can be deposited by sputtering Ti in the presence of nitrogen. The plasma can furnish energy to the N₂ to allow it to dissociate into atomic nitrogen, which then can easily react with the Ti. The reaction usually occurs either on the wafer surface or on the target itself, and not in the plasma.

[2]

Reactive sputter deposition is used for compound targets, like TiO₂. **[1]**

6. Describe 2 basic operational differences and similarities between CVD and ALD deposition processes. Write down 3 important benefits of ALD process.

Marks: 4+1.5=5.5

Ans:

Differences:

ALD reaction breaks the CVD reaction into two half-reactions, keeping the precursor materials separate during the reaction. In CVD, the cycles of transfer → adsorption → reaction → desorption happens almost simultaneously which is fast but with less conformality. ALD, though being a relatively slower process, is the most advanced deposition technique available of filling any aspect ratio structures and have perfect conformality. The chemical reaction is broken into elements steps - surface preparations → absorption → reaction → termination. ALD film growth is self-limited and based on surface reactions which allow to deposit 1 atom thick layer with every full deposition cycle.

[1+1 mark for stating any two differences]

Similarities:

ALD is actually a sub-set of CVD. Both encompasses deposition techniques in which the deposition depends on some sort of chemical reaction. Both of them starts with some sort of heat and mixing two vapors.

[1+1 mark for stating any two similarities]

3 Important Benefits of ALD:

- a. Atomic level of control over film composition.
- b. Uniform thickness over large areas and inside narrow holes.
- c. Very smooth surfaces (for amorphous films) with high density and few defects.

[0.5+0.5+0.5 mark for stating three important benefits]

9. What characterization tools (at least three) will you use to fabricate a MOS capacitor on Si(100) that would exhibit an **ideal-like capacitance-voltage (CV)** behavior with pre-estimated capacitance value and lowest possible leakage current. Briefly explain the role of each technique for characterizing a certain property of the MOS capacitor. You could use HfO_2 as an oxide.

Marks: 3+4.5=7.5

Ans:

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AFM = AFM can image surface of material in atomic resolution and also measure force at the nano-Newton scale.

SEM = SEM produces images of a sample by scanning the surface with a focused beam of electrons. The electrons interact with atoms in the sample, producing various signals that contain information about the surface topography and composition of the sample.

TEM = In the case of TEM, an image is formed from the interaction of the electrons with the sample as the beam is transmitted through the specimen. The image is then magnified and focused onto an imaging device, such as a fluorescent screen, a layer of photographic film, or a sensor such as a scintillator attached to a charge-coupled device.

XRR = The basic idea behind XRR is to reflect a beam of x-rays from a flat surface and to then measure the intensity of x-rays reflected in the specular direction (reflected angle equal to incident angle). If the interface is not perfectly sharp and smooth then the reflected intensity will deviate from that predicted by the law of Fresnel reflectivity. The deviations can then be analyzed to obtain the density profile of the interface normal to the surface.

SIMS = SIMS is the most sensitive of all the commonly employed surface analytical techniques - capable of detecting impurity elements present in a surface layer at < 1 ppm concentration, and bulk concentrations of impurities of around 1 ppb (part-per-billion) in favorable cases. This is because of the inherent high sensitivity associated with mass spectrometric-based techniques.

XPS = XPS is a surface-sensitive quantitative spectroscopic technique that measures the elemental composition at the parts per thousand range, empirical formula, chemical state and electronic state of the elements that exist within a material. Put more simply, XPS is a useful measurement technique because it not only shows what elements are within a film but also what other elements they are bonded to.

[1+1+1 mark for stating any three techniques]

[1.5+1.5+1.5 mark for explaining each of their role]