

4B22 – Flexible electronics CRIBS May 2017

1.

a)

A generic large-area electronic structure is composed of (1) a substrate, (2) backplane electronics, (3) a frontplane, and (4) encapsulation.

Backplanes provide or collect power and signal to or from front-planes. These may be passive or active. The ideal flexible active-matrix backplane should be rugged, rollable or bendable, capable of CMOS operation, and should lend itself to low-cost manufacturing. Today's TFT backplane technologies are best described by their active semiconductor, which may be amorphous, nanocrystalline, or polycrystalline silicon, a II–VI compound semiconductor, or an organic semiconductor in polymer or molecular form. As thin-film semiconductor technologies develop away from glass substrates and toward flexible substrates, the backplanes differentiate further by the type of substrate. The substrate material defines a region of TFT fabrication conditions in temperature–time space. The maximum tolerable process temperature is set by the type of substrate materials: < 300, < 600, and < 1,000°C for organic polymer, glass, and steel substrates, respectively.

Frontplanes carry the specific optoelectronic application. The frontplane materials of displays include liquid crystals for transmissive displays, reflective-mode liquid crystals and electrophoretic foils for reflective displays, and OLEDs for emissive displays. The frontplane might also be an X-ray sensor, an image sensor, a pressure sensor, a chemical sensor, an actuator or an artificial muscle in a smart textile.

b)

The students can choose one from the following main design strategies:

Stretchable wavy ribbons, in this case the ribbon is chemically bound to the substrate and no delamination occurs. These are fabricated by pre-stretching the PDMS substrate by a certain ΔL and then chemically bond metal ribbons are attached on the surface. Once the pre-strain is released, this will generate compression on the metal films producing waves. This stretchable technique has a great advantage to withstand both strain and compression, however buckling and complete detachment from the PDMS substrate may severely affect the stability of this option.

Pop up structures, the metal ribbon is chemically bond to the stretchable pre-strained substrate on at certain locations. This generates a controlled buckling once the strained substrate returns to its rest position. These sort of structures are fabricated by a process that precisely controls the thin film buckling on elastomeric substrates. Fabrication steps: i) Periodic activated and inactivated patterns are deposited on a pre-strained PDMS substrate. ii) a thin film parallel to the prestrain direction is deposited on top of the elastomeric substrate. The relaxation, compression and strain off the substrate give rise to buckling of the thin metal films.

Interconnects in the non co-planar mesh design consists of a mesh of stretchable interconnects and device islands. There device islands of rigid electronic chips are chemically bonded on a pre-strained PDMS substrate while the interconnects are loosely bonded. When the pre-strain in the substrate is released, the interconnects buckle out of the surface and form arc-shaped structures.

Six factors affect the built-in morphology of the gold films on PDMS:

- i) Gold film thickness, ii) the deposition temperature, iii) the secant modulus of the PDMS substrate.
- iv) the adhesion layer, v) preliminary surface treatments, vi) pre-stretch of the PDMS substrate.

c)

Enabling electronic circuits on flexible substrates can follow three main approaches. (i) The first is to transfer the existing high-temperature semiconductor technology to flexible substrates with high maximum working temperatures. However, high substrate and process costs restrict this technology to a limited number of applications, mainly very high added-value products, such as high-resolution flexible displays and high-end radio frequency (RF) ID tags. (ii) The second is to integrate high-performance devices on low-melting point

platforms is to reduce the maximum fabrication temperature of inorganic thin-film transistors to a level compatible with the thermal budget of the low-cost substrates. This approach has several advantages:

- wider variety of substrate materials available, including low-cost plastics, paper, or tissue;
- lower thermal budget materials can be integrated in the process, such as adhesives, polymers, and biomaterials;
- thermal deformations of the substrate are reduced, and so is mechanical stress occurring due to mismatch between thermal expansion coefficients of the substrate and the films;
- materials science, device physics, fabrication process, and equipment are already well established, for example, in a-Si technology.

For this approach due to the low maximum working temperatures of most low-cost plastics (the glass transition temperatures, T_g , in the range of 80–150°C), the thermal budget in the fabrication process is limited by 100–150°C. Process temperatures are too low to enable the manufacturing techniques developed for crystalline silicon, such as thermal oxidation, diffusion, or epitaxy resulting in the films having low mass density and high charge trapping, and their electronic properties are generally poor. The low thermal energy can be compensated by a soft bombardment by H⁺ ions enabling improved films conditions similar to those at higher temperature but without overheating the substrate.

(iii) The third is to use printing or coating deposition. These techniques are based on semiconductors in liquid form (i.e. dispersions or organic semiconductors) which can be patterned directly on a flexible substrate at low temperature.

Students can choose two from the following list of semiconducting materials deposited by low temperature:

- **Hydrogenated a-Si:H films:**

The degradation of PECVD Si thin-films is usually attributed to reduced surface mobility of the film-building radicals due to lower thermal energy on the growth surface. The thermal energy loss can be compensated by using “soft” ion H⁺ bombardment with the energy less than 50 eV, thus enabling the growth at low temperature. Hydrogenated a-Si can be deposited at substrate temperature as low as 35°C by use of hydrogen or helium dilution followed by post-deposition annealing at 150°C. The advantage is that show characteristics similar to those fabricated at 250-300°C with an optical bandgap between 1.7 and 1.9 eV. Drawback is that requires an ion bombardment and that is bound to standard Si deposition steps

- **Low temperature Nanocrystalline Silicon**

Nanocrystalline Si (nc-Si) is deposited at 75°C by PECVD. The crystalline size is in the 15-25nm range approaching crystalline purities of ~75%. This results in properties comparable with the high temperature counterpart (e.g. optical bandgap of ~1.9 eV). The advantages are that there is no requirement of pre-ion bombardment and that a high crystalline quality is achieved at high temperature. The disadvantages are in the growth of nc-Si seeds, in which a high growth rate is required.

- **Transition Metal Oxides**

Transition metal oxides (TMOs). TMO consist of one or more transition metals and oxygen. Some of the more common examples include zinc oxide, zinc tin oxide (ZTO), indium gallium zinc oxide (IGZO) and zinc indium oxide (ZIO). These are low-temperature amorphous materials can form the active material for transistors with a performance that significantly exceeds that of amorphous and nanocrystalline Si and approaches that of larger grain poly-Si without the complexities and uncontrolled variability of polycrystalline materials. A disadvantage in this case is the control their doping level during deposition due to electrically active defects formed during deposition. Printable forms of these materials have also been explored. Nanoparticles of ZnO have been used to form TFTs, but can require high temperature (>300°C) post-deposition anneals for the best performance.

- **Organic semiconductors**

Organic semiconductors comprise two broad classes of materials: molecular compounds and polymers. Both of these classes of materials generally have the feature of either a single conjugated unit or a number of conjugated units that form a planar molecular structure. There are many known semiconducting polymers, but those based on polymers of thiophene have generally been the most widely used for TFTs. Both p- and n-type organic materials have been demonstrated, thus organic materials may have an advantage over a-Si:H in applications where complementary logic is required. Disadvantage lies in the instability of the material at room temperature in air, thus requiring a capping or barrier for protection.

d)

Considering the following given parameters

Adhesion Energy $\gamma_{p,c} = 50 \text{ mJ m}^{-2}$

Thickness $h_p = 500 \text{ um}$

Thickness $h_c = 30 \text{ um}$

Length $L_p = 10 \text{ mm}$

Length $L_c = 10 \text{ mm}$

Young's modulus, $E_p = 135 - 160 \text{ kPa}$

Young's modulus, $E_c = 56 - 64 \text{ kPa}$

$$G = \frac{\bar{E}_p h_p \bar{E}_c h_c \varepsilon^2}{2 \left(1 - \frac{\bar{E}_p h_p L_p}{\bar{E}_p h_p + \bar{E}_c h_c L_c} \right)^2} \times \frac{\bar{E}_p h_p^3 + \bar{E}_c h_c^3}{(\bar{E}_p h_p^2 - \bar{E}_c h_c^2)^2 + 4 \bar{E}_p h_p \bar{E}_c h_c (h_p + h_c)^2}$$

To avoid delamination $G \leq \gamma_{p,c}$

So, we assume $G_{\text{limit}} = 50 \text{ mJ m}^{-2}$

By solving the various parts of the equation independently we obtain

$$A = \bar{E}_p h_p \bar{E}_c h_c = 134400000$$

$$B = 1 - \frac{\bar{E}_p h_p L_p}{\bar{E}_p h_p + \bar{E}_c h_c L_c} = 0.020568071$$

$$C = \bar{E}_p h_p^3 + \bar{E}_c h_c^3 = 20001512000$$

$$D = \bar{E}_p h_p^2 - \bar{E}_c h_c^2 = 39949600$$

$$E = \bar{E}_p h_p \bar{E}_c h_c (h_p + h_c)^2 = 3.7753E + 13$$

$$G_{\text{max}} = (A/2B) * C/(D^2+4E) * \varepsilon_{\text{max}}^2$$

$$\varepsilon_{\text{max}}^2 = G_{\text{max}} * (2B/A) * (D^2+4E/C)$$

$$\varepsilon_{\text{max}} = 3.66 - 4.06\%$$

Q1:

A popular and straightforward question, well-answered by most candidates who chose it. Few candidates gave incorrect list of “semiconducting materials” in (c), while some candidates found difficult the simple calculations required for (d).

2. a)

The starting point of the band model is the Schrodinger equation which can be mathematically treated in different ways. The nearly-free electron model assumes that the ions (positive charges) in the crystal lattice behave as perturbations in the uniform field in which the electrons can move. The Kronig-Penney model considers an additional periodic potential $U(x,y,z)$, to the Schrodinger equation which represents the ionic charges of the crystal lattice. The Schrodinger equation in the 1D form can be then rewritten as

$$\hat{H}\psi(\mathbf{r}) = \left(-\frac{\hbar^2}{2m}\nabla^2 + U(\mathbf{r}) \right) \psi(\mathbf{r}) = E\psi(\mathbf{r})$$

Where $U(\mathbf{r})$ has the periodicity of the Bravais lattice. The solutions to these equations are of the form:

$$\psi_k(\mathbf{r}) = u_k(\mathbf{r})\exp(i\mathbf{k} \cdot \mathbf{r})$$

Where \mathbf{k} is the wave vector, \mathbf{r} is a position in the Bravais lattice and $u_{\mathbf{k}}(\mathbf{r})$ is also a function with the periodicity of the Bravais lattice. The set of all wave vectors \mathbf{k} that yield plane waves with the periodicity of a given Bravais lattice is known as Reciprocal lattice. So, in general for a Bravais lattice position vector $\mathbf{R} = n_1\mathbf{a}_1 + n_2\mathbf{a}_2 + n_3\mathbf{a}_3$, $\mathbf{K} = h\mathbf{b}_1 + k\mathbf{b}_2 + l\mathbf{b}_3$ belongs to the reciprocal lattice of a Bravais lattice of points \mathbf{R} , provided that

$$e^{i\mathbf{K}\cdot(\mathbf{r}+\mathbf{R})} = e^{i\mathbf{K}\cdot\mathbf{r}}$$

holds for any \mathbf{r} and for all \mathbf{R} of the Bravais lattice.

The vectors in the reciprocal lattice exist in the momentum space (or k-space) which is the set of all momentum vectors a particle can have.

The electron's wavefunction is an oscillating wave with momentum \mathbf{k} . The electron energy is proportional to k^2 for free electrons, thus making it intuitive to plot E vs k .

b)

The energy of electrons in Trans-polyacetylene can be predicted by the equation below:

$$E = E_F \pm \sqrt{E_0^2 \cos^2(ka) + \left(\frac{E_g}{2}\right)^2 \sin^2(ka)}$$

Where E_F is the Fermi level, E_0 is the band size, E_g is the band gap and k is the momentum.

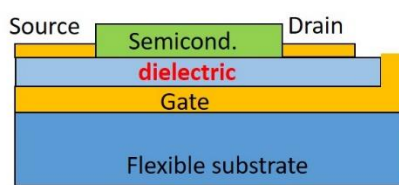
- a) For the number in the exercise this results in $E - E_f \sim 1.2$ eV.
- b) Considering the electron energy of $E - E_f = 2$ eV

$$\sqrt{E_0^2 \cos^2(ka) + \left(\frac{E_g}{2}\right)^2 \sin^2(ka)} = 2E$$

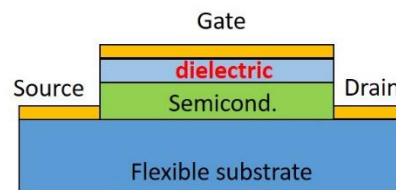
$$E_0^2 \cos^2(ka) + \left(\frac{E_g}{2}\right)^2 \sin^2(ka) = 4$$

Resolving the above we obtain $ka \sim 1.323$ rad.

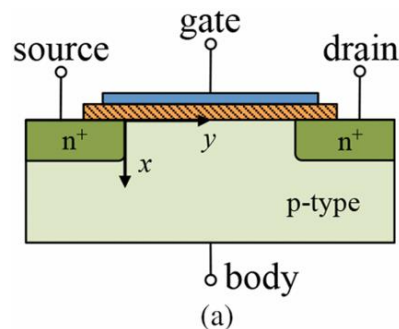
c)



Thin-Film Transistor (Bottom Gate)



Thin-Film Transistor (Top Gate)



Metal-oxide-semiconductor field-effect transistor (MOSFETs) are based on a rigid crystalline doped silicon wafer patterned with regions at different doping levels (n or p). MOSFETs generally operate in

inversion condition, where a conducting channel is formed under the gate dielectric layer and it is controlled by the V_g . The conductivity of the channel is controlled by the source and drain wells. A MOSFET device architecture is characterized by: *i*) a p-doped or n-doped semiconducting substrate or well; *ii*) highly doped regions underneath the source and drain electrodes of different polarity than the substrate or well where the device is obtained, *iii*) a thin gate oxide (e.g. SiO₂) in the active area between the source and drain electrodes and a gate electrode to generate a transversal electric field across the gate dielectric. This transversal electric field is responsible of the creation of an inversion region underneath the gate oxide which acts as a channel of opposite polarity than the well or substrate semiconductor where the device is obtained. As a consequence, by applying a potential difference between the drain and source, the corresponding electric charges are displaced throughout the channel and their rate is modulated through the potential difference between the gate and the well or the bulk substrate.

A Thin Film Transistor (TFT) is a layered structure on a neutral (plastic or glass) support substrate. A TFT is characterized by: a dielectric or intrinsic substrate where all active layers, including the semiconducting channel are deposited as thin film to form one of four possible staggered device architectures. More in details the following layers are deposited and patterned: i) source and drain contacts; ii) semiconducting channel, iii) gate dielectric, and iv) gate electrode. Their sequence can change according to different architectures of TFTs, e.g. bottom gate/bottom contacts (BGBC), bottom gate/top contacts (BGTC), top gate/bottom contacts (TGBC) or top gate/top contacts (TGTC). The gate dielectric layer is sandwiched between the gate electrode and a (generally amorphous or polycrystalline) thin semiconducting layer. TFTs normally operate in accumulation condition, whereby a concentration of charge carriers is accumulated at the semiconductor-insulator interface, thus determining the conductivity of the TFT channel.

In the standard MOSFETs the drain-current equations, μ_{FE} is a proportionality factor that relates the drain current I_D to the gate and drain voltages V_{GS} and V_{DS} , the threshold voltage V_t , the channel width W and length L , and the gate dielectric capacitance per unit area C_{ox} .

However, experimentally, the mobility in amorphous or organic TFTs is found to depend on V_{GS} and V_{DS} . Therefore, it is more straightforward to view it as a small-signal bias-dependent quantity, analogous to the small-signal gain of an amplifier rather than the large-signal quantity

The Thin film technology is independent of the substrate which plays no role in the determination of the electrical properties of the TFT.

d)

Percolation of sticks with monodisperse diameter can be written as:

$$N_C L^2 = 5.71$$

where N_C is the critical percolation threshold (minimum number of nanowires required to form a percolated network) and L is the length of the nanowires.

Thus, for sample A ($L=100 \text{ nm} = 1 \times 10^{-5} \text{ cm}$),

$$N_{CA} L^2 = 5.71$$

$$N_{CA} = \frac{5.71}{(1 \times 10^{-5})^2} / \text{cm}^2$$

$$N_{CA} = 5.71 \times 10^{10} / \text{cm}^2$$

i.e. 5.71×10^{10} number of wires will be required per cm^2 to establish a percolated network.

Similarly,

$$N_{CB} = \frac{5.71}{(0.7 \times 10^{-5})^2} = 11.65 \times 10^{10} / \text{cm}^2$$

$$N_{CC} = \frac{5.71}{(0.8 \times 10^{-5})^2} = 8.91 \times 10^{10} / \text{cm}^2$$

$$N_{CD} = \frac{5.71}{(0.6 \times 10^{-5})^2} = 15.86 \times 10^{10} / \text{cm}^2$$

Q2:

Popular question. Most of the candidates who attempted this question gave an incomplete answer for (a), but almost everyone could do (b) and (d). Mostly reasonably good answers in (c).

3. a)

The charge transport in conducting polymers is complex and can be modelled considering the band transport for intra polymer chains and hopping for both intrachain and interchain transport.

If an electric field is applied, the polarons present in the polymer travel through the chain in the direction of the electric field. However, misalignment of the polymeric chain, the absence of pure crystalline polymers and the electric field and the scattering of polarons with phonons limits the band transport in conducting polymers. The latter factor originates a temperature dependence on the mobility which scales as form $\mu \propto T^{-\nu}$ where $1 < \nu < 3$. This dependence can be shown to derive directly from the Einstein relation

$$\mu = \frac{De}{k_B T}$$

Where the diffusion coefficient $D = v \lambda_m$ might also be temperature dependant, where v is the drift velocity and λ_m is the mean free path. At higher temperatures more phonon modes are activated and the polarons will have a smaller mean free path. In conjugated polymers, for example, at temperature above the Debye temperature, the number of activated phonons increases linearly with temperature, more scattering is likely to occur, which gives rise to a $D \propto T^{-1}$ and thus μ which scales as T^{-2} .

b)

Using the Child's Law we have:

$$J_1 = \frac{9 \epsilon_r \epsilon_0 \mu_{eff1} V^2}{8 d^3}$$

$$J_2 = \frac{9 \epsilon_r \epsilon_0 \mu_{eff2} V^2}{8 d^3}$$

Where $\mu_{eff1} = \frac{n_1 - n_{trap1}}{n_1} \mu_1 = 2.2 \times 10^{-7} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$; and $\mu_{eff2} = \frac{n_2 - n_{trap2}}{n_2} \mu_2 = 8.653 \times 10^{-11} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$

Substituting the effective mobility in the Child's law equations we get $J_1 = 163.5 \text{ kA m}^{-2}$

And $J_2 = 64.31 \text{ A m}^{-2}$.

c)

The types of nanomaterials the students can choose three from are: carbon nanotubes, graphene, graphene oxide, Ag nanowires, metal nanoparticles.

A = Cathode, B = Anode

Conductive CNT coatings can be used transparent electrode for flexible photovoltaic devices based on wide range of methods including spraying, spin coating, casting, layer-by-layer, and Langmuir-Blodgett deposition.

Advantages: the work function of SWNT networks is in the 4.8 to 4.9 eV range which lays near to that of ITO (~4.7eV) ensuring an efficient electron collection. Another benefit is that SWNT films exhibit a high optical transparency in a broad spectral range from the UV-visible to the near-infrared range and highly flexibility, do not creep, do not crack after bending, theoretically have high thermal conductivities to tolerate heat dissipation, and have high radiation resistance. CNTs have also an ideal aspect ratio for percolation resulting in a low percolation threshold.

Disadvantages: The electrical sheet resistance of ITO is an order of magnitude less than the sheet resistance measured for SWNT electrodes. The electrode conductivity is hindered both by the junction resistance between two CNTs which is a contact point and results in increasing the overall contact resistance of a CNT film as well as the presence of both metallic and semiconducting type nanotubes. Moreover, the work function is still far from the 4.3eV of the electron transport layer thus limiting the electron transfer to CNT electrode.

Graphene films made from exfoliated graphite flakes are a good alternative to ITO for flexible solar cells. A sheet resistance of $30\Omega/\square$ and a transmittance of more than 90% make it attractive for transparent electrodes.

Advantages: Graphene films present a very low roughness being ideal for organic solar cells where pinholes in the photoactive layer have to be minimized. Moreover pristine graphene films require very easy production processing unlike CNTs or metal nanowires. The work function of graphene films in the range of 4.5eV 4.3eV make it superior to ITO and CNTs as a cathode for the specific application in figure 1, ensuring very good matching with the 4.3eV of the electron transport layer. Like CNTs graphene has a broadband transparency from UV to infrared wavelengths thus maximizing the solar spectrum absorption. The 2D nature of the graphene flakes reduces the inter-flake contact resistance with respect to CNTs, thus improving conductivity

Disadvantages: Graphene films from exfoliated flakes present a mixture of single and multilayers which has an impact on the overall work-function of the film, on the transmittance and on the electrical conductivity resulting in an increase of up to 2 orders (~3k Ω/\square) of magnitude. Graphene can be easily unintentionally doped by exposure to external environment or different organic compounds affecting the overall work-function. The presence of flakes smaller than 1 μ m increases the roughness of the film and reduces also the conductivity.

(An alternative discussion could be done on graphene oxide which present highly tunable work-function by chemical processing and large exfoliated flakes, >5 μ m, thus improving electron transfer and roughness of the film. However graphene oxide requires strong chemical reactions to retrieve electrical conductivity which might affect the overall device performances of the solar cell.)

Ag NWs have demonstrated to very good transparent and flexible electrodes and their metallic type ensures high conductivity at very low concentrations and excellent transparency thus. The work function of Ag NW is also in the 4.5 – 4.7 range and is suitable for an efficient electron transfer.

Advantages: Ag NWs like CNTs have a very good aspect ratio for percolation, thus requiring less NW concentration to achieve high conductivity of the film. Moreover, have sheet resistance in $m\Omega/\square$ range, which allows a film to easily achieve and improve the ITO values for sheet resistance with a less dense network with respect to CNTs, hence improving also the optical transmittance.

Disadvantages: The chemical instability of Ag might activate reaction processes that could lead to degradation of the flexible electrode and change of the work function. Moreover the 1D junction contact point between the NWs might increase the sheet resistance of the overall film. Ag has a higher scattering and reflectance than carbon base materials, thus resulting in a larger portion of the light being reflected from the transparent electrode and reduction of the overall solace cell efficiency. Moreover the cost of Ag NW compared to graphene and CNTs is at least one order of magnitude higher.

d)

Components:

A Indium Zinc Oxide (IZO) drain electrode;

B Indium Zinc Oxide (IZO) source electrode

C Indium Gallium Zinc Oxide semiconducting channel;

D Aluminium oxide gate dielectric layer;

E Ti/Au gate electrode;

F Ti/Au common source electrode.

On a glass or polymer substrate, neutralised by SiN_x or SiO_x, an indium gallium zinc oxide precursor solution is coated as a sol-gel form and photo-annealed in a N₂ atmosphere for a controlled time. Alternatively, a vacuum deposition technique (e.g. sputtering) can be used to deposit the metal-oxide layer. However the high temperature of these processes might affect the quality and density of the IGZO deposited layer, thus might not be suitable for low temperature flexible electronic substrates.

Q3:

Quite popular. Also in this case, most of the attempts to this question gave incomplete answers to (a), with only very few excellences. Most could do the standard bookwork of part (b) and (d). A good number of candidates gave the incorrect answer for the anode and cathode in the solar cell and some other few confused nanomaterials with semiconducting materials.

4)

a)

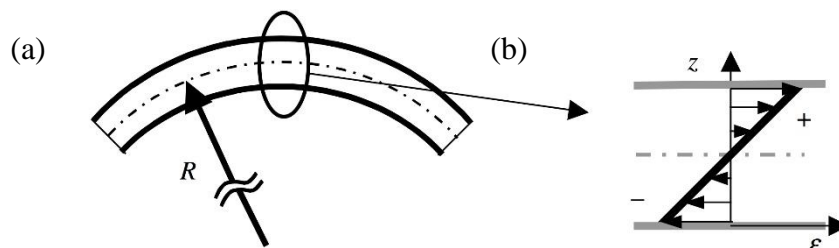


Figure 1: (a) sketch of the bent polymer film. (b) linear strain variation across the thickness of the polymer film.

The neutral plane for a uniaxially bent homogeneous polymer film denotes a plane parallel to its surfaces where the strain is zero. In the bent polymer film sketched in the above fig.1 (a), there will be compressive strain on top surface and tensile strain on the bottom surface. The strain variation across the thickness in a homogeneous polymer film will be linear, as shown in Fig 1(b). The neutral plane, marked by a dotted line in the centre along the thickness will therefore experience minimal strain.

b)

The neutral plane concept could be exploited to create a multilayer structure where the thin functional coating is embedded to reduce the strain on it. In its simplest form, it could be a three-layer structure, with thin coating

strategically placed in the middle of two identical layers. In a more practical design, the structure can consist of several layers, with the functional coating at the neutral strain plane.

Assumptions made: Linear mechanics, pure bending, and no-slip boundaries between the layers, and thus, zero shear deformation in the layers. No large mismatch between the elastic modulus of the layers.

c)

The plasma resonance frequency represents plasma oscillation of free carriers in a material. This plasma oscillation can screen incident EM waves via intraband transitions within the conduction band of the material. For the case of ITO, the electron density is smaller than metal, placing the plasma resonance frequency in the IR. This means that any incident IR radiation having longer wavelength than defined by the plasma resonance frequency is reflected back. Thus, the long wavelength (or infrared) edge of the optical transmission window of ITO is defined by this.

d)

The plasma oscillation frequency is given by:

$$\omega_p = \sqrt{\frac{ne^2}{\epsilon_0 m^*}}$$

$$2\pi f_p = \sqrt{\frac{ne^2}{\epsilon_0 m^*}}$$

where n is the density of electrons, e is the electron charge, m^* is the effective mass of electron and ϵ_0 is the permittivity of free space.

We get,

$$f_p = \frac{\sqrt{n} \times 1.602 \times 10^{-19} C}{2\pi \sqrt{9.109 \times 10^{-31} kg \times 8.854 \times 10^{-12} C^2 s^2 kg^{-1} m^{-3}}}$$

$$f_p = \frac{\sqrt{n} \times 1.602 \times 10^{-19} C}{2\pi \times 2.84 \times 10^{-21} Csm^{-3/2}}$$

$$f_p = \sqrt{n} \times 8980 cm^{\frac{3}{2}} s^{-1}$$

$$\frac{3 \times 10^{10}}{1400 \times 10^{-7}} = \sqrt{n} \times 8980 cm^{\frac{3}{2}} s^{-1}$$

(considering speed of light = 3×10^{10} cm/s)

$$n = 5.66 \times 10^{20} cm^{-3}$$

Q4:

Very popular question. Most of the candidates who selected this question produced very good solutions, except for part (c) where some gave missed to give a correct definition and formula for the plasma frequency, and could not relate it to the optical transmission window of Indium Tin Oxide.