Version FT/5

EGT3
ENGINEERING TRIPOS PART IIB

Thursday 4 May 2017 9.30 to 11

Module 4B22

FLEXIBLE ELECTRONICS

*Answer not more than **three** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

*Write your candidate number **not** your name on the cover sheet.*

STATIONERY REQUIREMENTS

Single-sided script paper

Graph paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM

CUED approved calculator allowed

Engineering Data Book

Attachment: 4B22 Flexible Electronics data sheet (1 page)

10 minutes reading time is allowed for this paper.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

1 (a) List the four layers composing a flexible electronic system. What is the role of the back-plane and front-plane in enabling flexible electronic displays? [20%]

(b) Describe one design strategy enabling stretchable electronic interconnects. What are the factors affecting the morphology of gold thin-films on Poly-dimethylsiloxane (PDMS)? [20%]

(c) Discuss the need for low temperature processing in flexible electronics manufacturing. List two semiconducting materials for flexible electronics that can be processed at low temperature and discuss their respective advantages and disadvantages. [25%]

(d) A hybrid stretchable strain sensor device is composed of a 1.0 cm strip of electrically conductive carbon-black doped silicone (CPDMS) deposited onto PDMS substrate. Given a thickness of h_C = 30 μm for the CPDMS and h_P = 0.5 mm for the PDMS, and the elastic properties of the two materials as shown in Figure 1, estimate the approximate value of the in-plane Young's moduli $\bar{E}_p$ and $\bar{E}_c$ from the graphs.

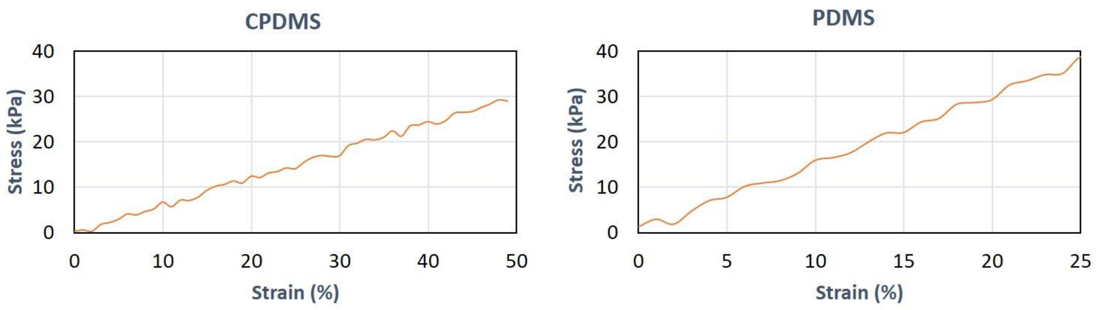

Figure 1

Obtain the maximum in-plane tensile strain ε_{max} that will induce delamination of the CPDMS strip from the substrate, knowing the formula of the driving force for interfacial delamination:

$$G = \frac{\bar{E}_P h_P \bar{E}_C h_C \varepsilon^2}{2\left(1 - \frac{\bar{E}_P h_P}{\bar{E}_P h_P + \bar{E}_C h_C}\frac{L_P}{L_C}\right)^2} \times \frac{\bar{E}_P h_P^3 + \bar{E}_C h_C^3}{(\bar{E}_P h_P^2 - \bar{E}_C h_C^2)^2 + 4\bar{E}_P h_P \bar{E}_C h_C (h_P + h_C)^2}$$

Where L_p=L_c is the length of the corresponding sections subject to the tensile strain, and $\gamma_{P,C}$ = 50 mJ/m^2 is the adhesion energy between the PDMS and the CPDMS. [35%]

2 (a) Discuss the key assumptions made when deriving the general electronic band model. Explain what the *k*-space is. Why is the electron energy plotted against the *k*-space instead of the real space? [25%]

(b) The band-gap of *trans*-polyacetylene is E_g = 1.5 eV and the band size E_0 = 6.4 eV. If an electron energy E is defined by $ka = 14\pi/30$, where k is the momentum and a is the lattice spacing, determine what is the value of E relative to the Fermi energy E_F. What is the value of ka for an energy of $2E$? [30%]

(c) Sketch and compare a Thin Film Transistor (TFT) architecture with a Metal Oxide Semiconductor Field Effect Transistor (MOSFET), highlighting the key differences in terms of the charge transport and the enabling factors for flexible electronics. [25%]

(d) Consider four liquid dispersions (A, B, C, D) of silver nanowires with the same mean-squared diameter and the lengths shown in Table 1:

	A	B	C	D
Length (nm)	100	70	80	60

Table 1

Assuming the nanowires as sticks and their uniform deposition as thin-film, calculate the critical percolation threshold for the four thin-films in terms of the number of nanowires per unit area. [20%]

3 (a) Explain why the carrier mobility μ in conducting polymers might follow the form $\mu \propto T^{-2}$ at high temperatures. How does the thermal energy affect the electron transfer process in conducting polymers? [25%]

(b) A potential difference of V_d = 6 V is applied across a semiconducting polymer layer of thickness d = 135 nm and dielectric constant ε_r = 5.1. The transport properties of the polymer with two different doping levels are: in the first case a charge density of $n_1 = 1.7 \times 10^{23}$ m^{-3} a trap density of $n_{trap1} = 6.8 \times 10^{10}$ m^{-3} and a mobility $\mu_1 = 2.2 \times 10^{-7}$ m^2 V^{-1} s^{-1}. In the second case a charge density of $n_2 = 2.6 \times 10^{20}$ m^{-3}, a trap density of $n_{trap2} = 1.4 \times 10^{18}$ m^{-3} and a mobility $\mu_2 = 8.7 \times 10^{-11}$ m^2 V^{-1} s^{-1}. Calculate the corresponding fluxes, j_1 and j_2, for the first and second case, using Child's law. [20%]

(c) Briefly discuss how the dimensionality of nanomaterials affects the macroscopic electrical properties of flexible electrodes. Figure 2 shows the flat-band energy level diagram of a flexible thin film solar cell. A transparent silver electrode is selected as the flexible anode. Between A and B electrodes, which is the cathode and which is the anode? List three types of nanomaterials that could be used as the flexible cathode. Briefly describe their advantages and disadvantages for the specific case. [30%]

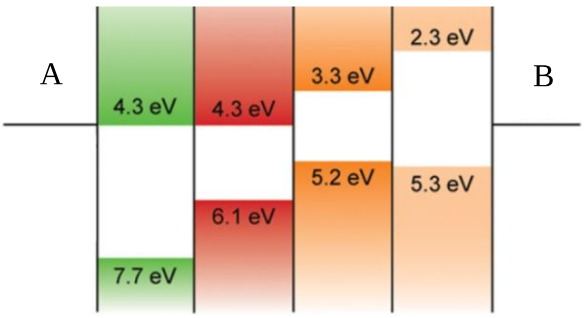

Figure 2

(d) Identify the components and materials marked A-F in the Indium Gallium Zinc Oxide (IGZO) TFT shown in Figure 3. Describe a suitable deposition technique for the IGZO layer on a flexible substrate and explain why this is a preferred option. [25%]

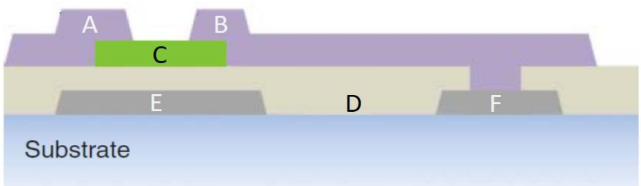

Figure 3

4 (a) Sketch and explain the strain distribution across the perpendicular section of a uniaxially bent film. Identify what is the neutral plane of such a bent film. [25%]

(b) How can the concept of neutral plane be used to reduce the strain on a large area thin functional coating deposited on a flexible substrate under uniaxial bending? State any assumptions made. [25%]

(c) What is the plasma resonance frequency and how is it related to the optical transmission window of Indium Tin Oxide (ITO)? [20%]

(d) An ITO film is to work as a transparent conductor for values of wavelength up to 1400 nm. What is the maximum free carrier density allowed in the film? [30%]

END OF PAPER

ANSWERS:

Q1.

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

b) 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) Students can choose the description of two of the following list of semiconducting materials deposited by low temperature:

- **Hydrogenated a-Si:H films:**
- **Low temperature Nanocrystalline Silicon**
- **Transition Metal Oxides**
- **Organic semiconductors**

d) Range of values: Young's modulus, Ep = 135 – 160 kPa, Young's modulus, Ec = 56 – 64 kPa.
ε_{max}= 3.66 – 4.06%

Q2.

a) Discussion about Shroedinger equation and Bloch's theorem.

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 k. The electron energy is proportional to k2 for free electrons, thus making it intuitive to plot E vs k.

b) $E-E_f$ ~1.2 eV. Ka~ 1.323 rad.
c) Sketch and comparison TFT vs MOSFET.
d)

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

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

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

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

Q3.

a) Discussion about transport in conjugated polymers.

$$\mu = \frac{De}{k_B T}$$ where $\mu \propto T^{-\nu}$ where $1 < \nu < 3$.

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)

J_1=163.5 kA m^{-2} and J_2= 64.31 A m^{-2}.

c)

A = Cathode, B = Anode

Discussion about dimensionality affecting the electrical properties of electrodes with a specific comment to application in solar cells.

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 SiNx or SiOx, an indium gallium zinc oxide precursor solution is coated as a sol-gel form and photo-annealed in a N_2 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.

Q4.

a)

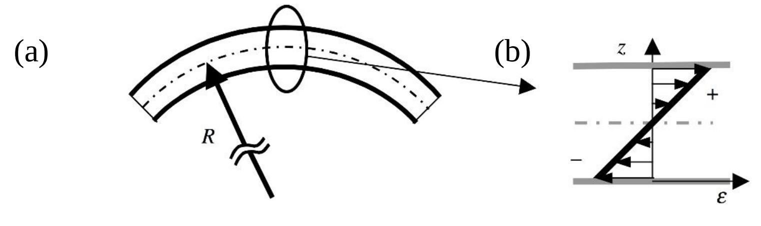

Figure 2: (a) sketch of the bent polymer film. (b) linear strain variation across the thickness of the polymer film.

b)

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.

d)

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