Question 1 [9 marks]:

a) Figure 1 shows a bottom-gate, bottom-contact (BGBC) thin film transistor (TFT) substrate. We apply a gate-source bias to this device and measure the gate current \( I_G \), as shown in Figure 1(c). Using the information in this figure, state the leakage current density and breakdown field \( E_B \) for this dielectric. Give your answers in mA/cm\(^2\) and MV/cm respectively. [4 marks]

Looking at Figure 1(b), we see that a BGBC TFT is basically a metal-insulator-metal diode and can be treated the same way. We are asked to evaluate the leakage current density and the breakdown field strength from Figure 1(c). The leakage is current is the current flows through the dielectric under normal conditions. From Figure 1(c), we see this is roughly \( 3 \times 10^{-10} \) A. We are asked for current density, so we need to normalize for area. The electrode area is not given explicitly, but we can work out the area of the source electrode from the top-down view (Figure 1(a)). We can break it down into two rectangles (green and black) as show below:

Work in cm. The area of the green rectangle is:

\[
A_1 = 0.03 \times 0.08 = 0.0024 \text{ cm}^2
\]
The area of the green black rectangle:

\[ A_2 = 0.005 \times 0.1 = 0.0005 \text{ cm}^2 \]

So the total electrode area is hence:

\[ A = A_1 + A_2 \]
\[ A = 0.0024 + 0.0005 = 0.0029 \text{ cm}^2 \]

We can therefore say the leakage current density is:

\[ J = \frac{3 \times 10^{-10}}{0.0029} = 103 \text{ nA/cm}^2 \]

The electric field strength is given by the voltage applied divided by the distance over which it is applied:

\[ E = \frac{V}{d} \]

We see that the 200nm dielectric breaks down at 40V. Hence we can say the breakdown field is:

\[ E_d = \frac{V}{d} = \frac{40}{200 \times 10^{-7}} = 2 \times 10^6 \text{ V/cm} = 2 \text{ MV/cm} \]

b) Explain why you would want a high capacitance dielectric for portable devices.[1 marks]

Portable devices need to be powered by batteries, and hence they need to operate at low voltages. We know the charge density \( Q \) induced in a TFT is linearly proportional to both applied gate voltage \( V_G \) and areal capacitance \( C_{ox} \):

\[ Q = C_{ox} V_G \]

For a device to operate with the same charge density (i.e. able to supply the same current), with a reduced voltage, it would have to require an increased capacitance.

c) Consider a TFT that employs a 100 nm-thick Hafnium Oxide (HfO2), which has a threshold voltage of \( V_T = -5 \text{ V} \). For an applied gate voltage of \( V_G = +5 \text{ V} \), and zero drain voltage \( V_D = 0 \text{ V} \) determine the mobile 2-dimensional carrier number-density. You can assume the dielectric constant of HfO2 is 25. Give your answer in cm\(^2\).[3 marks]

You will need:
- Vacuum permittivity \( \varepsilon_0 = 8.85 \times 10^{-12} \text{ F/m} \).
• Fundamental unit of charge $e = 1.60 \times 10^{-19} \text{C}$.

From Lecture 3 we know the mobile carrier density ($Q_{mob}$) in a TFT is given by:

$$Q_{mob} = C_{ox}(V_G - V_T)$$

Where the dielectric capacitance per unit area is given by:

$$C_{ox} = \frac{\varepsilon_0 \kappa}{d}$$

We are told the relativity permittivity: $\kappa = 25$, the dielectric thickness is 100nm, and the vacuum permittivity ($\varepsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$). Since we are given the vacuum permittivity in SI units we need to be consistent. So here we will first evaluate the capacitance in units of F/m$^2$:

$$C_{ox} = \frac{8.85 \times 10^{-12} \times 25}{10^{-7}} = 2.21 \times 10^{-3} \text{ F/m}^2$$

In units of F/cm$^2$ this is:

$$C_{ox} = 2.21 \times 10^{-7} \text{ F/cm}^2$$

Now we can evaluate the mobile charge density:

$$Q_{mob} = C_{ox}(V_G - V_T)$$

$$Q_{mob} = 2.21 \times 10^{-7} \times (5 - 5) = 2.21 \times 10^{-6} \text{ C/cm}^2$$

We are asked for the number density of mobile charges, not the charge density. We know the number density of charges ($n$) is the total charge density divided ($Q_{mob}$) by the charge per particle ($e$):

$$n = \frac{Q_{mob}}{e}$$

We are given the fundamental unit charge:

$$n = \frac{2.21 \times 10^{-6}}{1.60 \times 10^{-19}} = 1.38 \times 10^{13} \text{ cm}^{-2}$$

d) Describe a situation in which it would be useful to employ a cross-linkable polymer as a gate dielectric.[1 mark]

For electronics to be compatible with large-area, low-cost deposition techniques such as roll-to-roll printing, TFTs must fully solution-processable. For this to possible we need to deposit solution-processed semiconductors on solution-processable gate dielectrics (or vice-versa). This requires that the solvent used in the top layer does not dissolve and disrupt the layers below it. One option is to use a dielectric that becomes insoluble once exposed to heat or UV radiation. A cross-linkable dielectric is such an example, and allows one to deposit a dielectric from solution, cure it to become insoluble, then deposit a solution-processable semiconductor on top without causing damage the dielectric.
Question 2 [9 marks]:

a) Consider an interface between a source / drain electrode and a semiconductor which we can describe entirely by thermionic emission. Calculate the contact resistance of this interface if:

- the barrier height voltage is 50 mV,
- the temperature is 300K,
- the effective mass of the semiconductor is 0.3\( m_e \) (where \( m_e \) is the rest mass of an electron in a vacuum),
- and the electrode contact area is \( 5 \times 10^{-4} \) cm\(^2\).[4 marks]

You will need:

- Fundamental unit of charge: \( q = 1.60 \times 10^{-19} \) C.
- Boltzmann Constant: \( k_B = 1.38 \times 10^{-23} \) J/K.
- Pi: \( \pi = 3.14 \).
- Planck Constant: \( h = 6.63 \times 10^{-34} \) J/s.
- Rest mass of electron in vacuum: \( m_e = 9.11 \times 10^{-31} \) kg.

We are told we can describe the interface entirely by thermionic emission, we can hence use the following equation for specific interfacial resistance (\( \rho_i \)):

\[
\rho_i = \rho_1 \exp \left( \frac{q\Phi_B}{k_B T} \right)
\]

The prefactor is given by:

\[
\rho_1 = \frac{k_B}{qA^*T}
\]

And Richardson’s Constant is:

\[
A^* = \frac{4\pi q k_B^2 m^*}{h^3}
\]

Basically this is an exercise in entering constants. Let’s start by evaluating Richardson’s Constant. We will stick to SI units:

\[
A^* = \frac{4\pi q k_B^2 m^*}{h^3} = \frac{4 \pi \times 1.6 \times 10^{-19} \times (1.38 \times 10^{-23})^2 \times 0.3 \times 9.11 \times 10^{-31}}{(6.63 \times 10^{-34})^3} = 3.59 \times 10^5 \text{Am}^{-2}\text{K}^{-2}
\]

We can then evaluate the prefactor to the specific interfacial resistivity:

\[
\rho_1 = \frac{1.38 \times 10^{-23}}{1.6 \times 10^{-19} \times 3.59 \times 10^5 \times 300} = 8.01 \times 10^{-13} \text{\Omega m}^2
\]

We can now convert to \( \Omega \)cm\(^2\):

\[
\rho_1 = 8.01 \times 10^{-9} \text{\Omega cm}^2
\]

Now we can evaluate the specific interfacial resistivity:
\[ \rho_i = 8.01 \times 10^{-9} \times \exp \left( \frac{1.60 \times 10^{-19} \times 0.05}{1.38 \times 10^{-23} \times 300} \right) = 5.53 \times 10^{-8} \ \Omega \text{cm}^2 \]

The contact resistance \((R_C)\) is related to the specific interfacial resistivity via the below equation:

\[ R_C = \frac{\rho_i}{A} \]

Where \(A\) is the interfacial contact area. We are told the contact area is 0.005 cm\(^2\). Hence the contact resistance is:

\[ R_C = \frac{5.53 \times 10^{-8}}{5 \times 10^{-4}} = 1.11 \times 10^{-4} \ \Omega = 111 \mu\Omega \]

I.e. a very low resistance.

b) A transfer-length measurement is carried out on the sample shown in Figure 2. The voltage applied between each terminal was kept constant at 10V and the current was measured as a function of electrode separation for each pair of electrodes. The results are shown in the below table. From this data approximate the contact resistance in this structure.[5 marks]

![Figure 2 Top-down view of transfer-length structure for measuring contact resistance, with distances between electrodes given.](image)

<table>
<thead>
<tr>
<th>Separation (μm)</th>
<th>Current (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>40</td>
<td>2.5</td>
</tr>
<tr>
<td>60</td>
<td>1.67</td>
</tr>
<tr>
<td>80</td>
<td>1.25</td>
</tr>
</tbody>
</table>

We need to use the equation for the total resistance between any two terminals \((R_T)\):

\[ R_T = \frac{R_{sh}d_i}{Z} + 2R_C \]

Where \(R_{sh}\) is the sheet resistance of the material, \(d_i\) is the distance between electrodes, \(Z\) is the width of the electrodes and \(R_C\) is the contact resistance. We can identify this as the equation for a straight line:
\[ y = mx + c \]

So by plotting measured \( R_T \) on the \( y \) axis and separation on the \( x \) axis, we can evaluate the \(-\) intercept with the \( y \)-axis as \( 2R_c \).

We first need to evaluate total measured resistance from current using \( V = IR \):

<table>
<thead>
<tr>
<th>Separation (μm)</th>
<th>Current (μA)</th>
<th>Resistance (MΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>40</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>60</td>
<td>1.67</td>
<td>5.99</td>
</tr>
<tr>
<td>80</td>
<td>1.25</td>
<td>8</td>
</tr>
</tbody>
</table>

We can now plot measured resistance as a function of separation:

We need to fit a straight line to these points to evaluate the contact resistance. It will look something like this:
From this graph it is very hard to see where the fit hits the \( y \)-axis, but from the Excel spreadsheet (or whatever fitting software you use), you can get the intercept. It should come out to about:

\[
2R_e = 100\Omega
\]

So we find:

\[
R_e = 50\Omega
\]

**Question 3 [7 marks]:**

a) Consider an ambipolar TFT which has a threshold voltage for electrons of \( V_{Te} = +7.5 \text{ V} \) and a threshold voltage for holes of \( V_{Th} = -10 \text{ V} \). If you apply a gate voltage of \( V_G = +25\text{V} \), state the range of drain voltages you would have to apply to the TFT to observe that the electron channel is saturated but there are no holes in the channel (i.e. the drain voltage required to observe conventional unipolar saturation regime)? [3 marks]

Here we are applying a positive gate bias, and we can hence consider electrons to be the majority carrier. We are told the threshold voltage for electrons is \( V_{Te} = +7.5\text{V} \), and we are applying a gate voltage of \( V_G = +25\text{V} \), \( V_G > V_{Te} \) and we can hence expect electrons to be injected from the source electrode.

So we just need to consider what biasing conditions are required to inject holes from the drain into the channel. We know from Lecture 12 that the majority carrier (i.e. electrons in our case) channel needs to be saturated for there to be room for the minority carrier in the channel. So we hence need to apply a drain voltage that is:

\[
V_D > V_G - V_{Te}
\]

We are told both the applied gate voltage and the threshold voltage for electrons:

\[
V_D > 25 - 7.5
\]
\[
V_D > 17.5 \text{ V}
\]

As always, if we are interested in injection from the drain we need to consider voltages relative to the potential at the drain terminal. I.e. we need to carry out a voltage transformation. Sometimes it is easier to draw a picture to visualize the transformation:

![Diagram](image-url)

So looking from the prospective of the drain (D) electrode, we need the relative voltage at the gate to be lower than the threshold voltage for injection for holes. I.e. we need:
\[ V_G - V_D < V_{Th} \]

I.e. we need our drain voltage to be:

\[ V_D > V_G - V_{Th} \]

We are told both the applied gate voltage and the threshold voltage for holes:

\[ V_D > 25 - (-10) \]

\[ V_D > 35 \text{ V} \]

This is the voltage we need to see holes in the channel. To see no holes we hence require:

\[ V_D < 35 \text{ V} \]

So to see the channel saturated and free of holes, we would require:

\[ 17.5 \text{ V} < V_D < 35 \text{ V} \]

b) **Explain briefly why you cannot used the gradual channel approximation to extract mobility in the saturation regime in ambipolar TFTs.** [2 marks]

In a unipolar TFT if you apply a drain voltage that is high enough (|\(V_D| > |V_G - V_{Th}|\)) you expect the channel to saturate, and for voltages where |\(V_D| > |V_G - V_{Th}|\), the effective device voltage applied across the device is just \(V_D = V_G - V_{Th}\). In the gradual channel approximation (GCA) we state that under these conditions \(V_D\) is a constant at \(V_G - V_{Th}\). We use this approximation to derive an equation for mobility in the saturation regime:

\[
\mu_{sat} = \frac{2L}{WC_{ox}} \left( \frac{d\sqrt{I_D}}{dV_G} \right)^2 = \frac{2L}{WC_{ox}} \frac{d^2I_D}{dV_G^2}
\]

While there may be a region where the TFT does saturation, in ambipolar TFTs there is the possibility that both carriers are present at the same time. Once both carriers are present simultaneously, the TFT is no longer saturated, and returns to exhibiting a linear increase in current with applied drain voltage. Under these conditions we cannot say the effective drain voltage across the channel is constant at \(V_D = V_G - V_{Th}\), and hence cannot use the result of the GCA as described above.

c) **Explain briefly why you may expect light emission to take place from certain ambipolar TFTs.** [2 marks]

Under certain conditions we can expect both holes and electrons to be present in the channel simultaneously. One carrier type (majority) will be injected from the source electrode and one carrier type (minority) will be injected from the drain electrode. Because holes and electrons have opposite charges they will travel in opposite directions under the same voltage. When electrons and holes meet the recombine / annihilate in the semiconductor. If the recombination is radiative then recombination will lead to the emission of optical photons and hence light.