Useful Constants:

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Permittivity</td>
<td>( \varepsilon_0 )</td>
<td>( 8.85 \times 10^{-12} ) F/m</td>
</tr>
<tr>
<td>Fundamental Unit of Charge</td>
<td>( e )</td>
<td>( 1.60 \times 10^{-19} ) C</td>
</tr>
<tr>
<td>Boltzmann Constant</td>
<td>( k_B )</td>
<td>( 1.38 \times 10^{-23} ) J/K</td>
</tr>
<tr>
<td>Planck Constant</td>
<td>( h )</td>
<td>( 6.63 \times 10^{-34} ) Js</td>
</tr>
<tr>
<td>Pi</td>
<td>( \pi )</td>
<td>3.14</td>
</tr>
<tr>
<td>Rest Mass of Electron in Vacuum</td>
<td>( m_e )</td>
<td>( 9.11 \times 10^{-31} ) kg</td>
</tr>
<tr>
<td>Speed of light in vacuum</td>
<td>( c )</td>
<td>( 3.00 \times 10^8 ) m/s</td>
</tr>
</tbody>
</table>

Useful Equations:

**Capacitance per Unit Area of Parallel Plate Capacitor:**

\[
C = \frac{\varepsilon_0 \kappa}{d}
\]

- \( C \) is the capacitance per unit area.
- \( \varepsilon_0 \) is the vacuum permittivity.
- \( \kappa \) is the relative permittivity.
- \( d \) is the separation distance of the plates.

**Gate-Induced Mobile Charge Density in TFT:**

\[
Q_{mob} = C(V_G - V_T)
\]

- \( Q_{mob} \) is the areal charge density of induced carriers.
- \( C \) is the capacitance per unit area.
- \( V_G \) is the applied gate voltage.
- \( V_T \) is the TFT threshold voltage.

**Characteristic Energy of Metal Semiconductor Interface:**

\[
E_{00} = \frac{e h}{4\pi} \sqrt{\frac{n}{\varepsilon_0 \varepsilon_r m_{tun}^*}}
\]

- \( E_{00} \) is the characteristic energy of the interface.
- \( e \) is the fundamental unit of charge.
- \( h \) is the Planck Constant.
- \( n \) is the free carrier density in the semiconductor.
- \( \varepsilon_0 \) is the vacuum permittivity.
- \( \varepsilon_r \) is the relative permittivity of the semiconductor.
- \( m_{tun}^* \) is the effective mass of tunneling.
Energy of Photon:
\[ E = \frac{hc}{\lambda} \]
- \( E \) is the photon energy.
- \( h \) is the Planck Constant.
- \( c \) is the speed of light in a vacuum.
- \( \lambda \) is the wavelength of the light.

Relationship between Frequency and Wavelength of Light:
\[ v = \frac{c}{\lambda} \]
- \( v \) is the photon frequency.
- \( c \) is the speed of light in a vacuum.
- \( \lambda \) is the wavelength of the light.

Binding Energy of Electrons as Determined by Ultraviolet Photoemission Spectroscopy:
\[ E_B = h\nu - KE - e\phi_{sp} \]
- \( E_B \) is the binding energy of photo-emitted electrons.
- \( h \) is the Planck Constant.
- \( \nu \) is the photon frequency of incident UV photons.
- \( KE \) is the kinetic energy of detected electrons.
- \( e \) is the magnitude of the fundamental unit of charge.
- \( \phi_{sp} \) is the workfunction of the detector in Volts.

Smits Model for n-type Unipolar TFT:
\[ I_D = \gamma \frac{W}{L} \frac{T}{2T_0} \frac{T}{2T_0 - T} \left[ (V_G - V_T)^{2T_0/T} - (V_G - V_T - V_D)^{2T_0/T} \right] \]
- \( I_D \) is the source-drain current.
- \( \gamma \) is the gamma parameter for electrons in this semiconductor.
- \( W \) is the transistor channel width.
- \( L \) is the transistor channel length.
- \( T \) is the temperature.
- \( T_0 \) is the characteristic temperature describing the width of electron states of this semiconductor.
- \( V_G \) is the applied gate voltage.
- \( V_T \) is the threshold voltage.
- \( V_D \) is the applied drain voltage.

Smits Model for p-type Unipolar TFT:
\[ I_D = \gamma \frac{W}{L} \frac{T}{2T_0} \frac{T}{2T_0 - T} \left[ (V_T - V_G)^{2T_0/T} - (V_T - V_G + V_D)^{2T_0/T} \right] \]
- \( I_D \) is the source-drain current.
- \( \gamma \) is the gamma parameter for holes in this semiconductor.
- \( W \) is the transistor channel width.
- \( L \) is the transistor channel length.
• $T$ is the temperature.
• $T_0$ is the characteristic temperature describing the width of hole states of this semiconductor.
• $V_G$ is the applied gate voltage.
• $V_T$ is the threshold voltage.
• $V_D$ is the applied drain voltage.

Smits Model for Ambipolar TFT with Electron Majority Carriers:

$$I_D = \frac{W}{L} \left[ \gamma_e \frac{T}{2T_{0e}} \frac{T}{T_0e - T} (V_G - V_T)^{2T_{0e}/T} + \gamma_h \frac{T}{2T_{0h}} \frac{T}{2T_{0h} - T} (V_D - V_G + V_T)^{2T_{0h}/T} \right]$$

• $I_D$ is the source-drain current.
• $W$ is the transistor channel width.
• $L$ is the transistor channel length.
• $T$ is the temperature.
• $\gamma_e$ is the gamma parameter for electrons in this semiconductor.
• $\gamma_h$ is the gamma parameter for holes in this semiconductor.
• $T_{0e}$ is the characteristic temperature describing the width of electron states of this semiconductor.
• $T_{0h}$ is the characteristic temperature describing the width of hole states of this semiconductor.
• $V_G$ is the applied gate voltage.
• $V_T$ is the threshold voltage.
• $V_D$ is the applied drain voltage.

Smits Model for Ambipolar TFT with Hole Majority Carriers:

$$I_D = \frac{W}{L} \left[ \gamma_h \frac{T}{2T_{0h}} \frac{T}{2T_{0h} - T} (V_T - V_G)^{2T_{0h}/T} + \gamma_e \frac{T}{2T_{0e}} \frac{T}{2T_{0e} - T} (V_T - V_G + V_D)^{2T_{0e}/T} \right]$$

• $I_D$ is the source-drain current.
• $W$ is the transistor channel width.
• $L$ is the transistor channel length.
• $T$ is the temperature.
• $\gamma_e$ is the gamma parameter for electrons in this semiconductor.
• $\gamma_h$ is the gamma parameter for holes in this semiconductor.
• $T_{0e}$ is the characteristic temperature describing the width of electron states of this semiconductor.
• $T_{0h}$ is the characteristic temperature describing the width of hole states of this semiconductor.
• $V_G$ is the applied gate voltage.
• $V_T$ is the threshold voltage.
• $V_D$ is the applied drain voltage.

External Quantum Efficiency of Phototransistor:

$$\eta = \frac{(I_{D,\text{ill}} - I_{D,\text{dark}})hc}{ePLW}$$

• $\eta$ is the external quantum efficiency (EQE) of the phototransistor. EQE is between 0 and 1.
• $I_{D,\text{ill}}$ is the source-drain current under illumination.
• $I_{D,\text{dark}}$ is the source-drain current in the dark.
• $h$ is the Planck Constant.
• $c$ is the speed of light in a vacuum.
• $e$ is the fundamental unit of charge.
• $P_i$ is the optical power density incident on the transistor channel.
• $W$ is the transistor channel width.
• $L$ is the transistor channel length.

**Strain:**

$$\varepsilon = \frac{L_n - L_0}{L_0}$$

• $\varepsilon$ is the strain in the deformation direction.
• $L_0$ is the original object length.
• $L_n$ is the object length after deformation.

**Stress:**

$$\sigma = \frac{F}{A}$$

• $\sigma$ is the stress in the direction of applied force.
• $F$ is the force applied to the object.
• $A$ is the cross-sectional area of the object.

**Young’s Modulus:**

$$Y = \frac{\sigma}{\varepsilon}$$

• $Y$ is the Young’s modulus of the material.
• $\sigma$ is the stress in the direction of applied force.
• $\varepsilon$ is the strain in the deformation direction.
Question 1 [10 marks]:

a) The Figure below shows some example TFT transfer data. Assume that $I_D$ is the source-drain current, and $I_G$ is the source-gate leakage current. If the transistor source electrode has an area of 0.005 cm$^2$, what is the maximum leakage current density measured? Give your answer in A/cm$^2$. [2 mark]

b) The figure below shows the current measured as a function of applied voltage for a metal-insulator-metal capacitor with an 80nm thick insulator layer. The red arrows indicate the measurement direction. From this data, approximate the breakdown field strength. Give your answer in MV/cm. If this breakdown process was reversible, state what differences you would expect to see in this figure. [3 marks]

c) Consider the self-assembled monolayer: octadecyl-acrylamide (ODA), whose molecular structure is shown in the figure below. If ODA was used as a gate dielectric on its own (i.e. not on top of Al$_2$O for example), calculate the voltage required to induce a mobile carrier number density of $1.1 \times 10^{13}$ cm$^{-2}$. Assume the threshold voltage for this TFT is zero and the relative permittivity of this molecule is $\kappa = 3$. For this calculation you can approximate all carbon atoms as being in a straight line with a carbon-carbon and carbon-nitrogen bond length of 150 pm, and you can neglect hydrogen atoms. Explain why this is likely to be an over-estimate of the operation voltage. [4 marks]
d) Provide a possible explanation for the observation that metal-oxide TFTs employing high-\(\kappa\) dielectrics such as HfO\(_2\) or ZrO\(_2\) exhibit higher charge-carrier mobilities than those employing conventional dielectrics such as SiO\(_2\) for example.[1 mark]

**Question 2 [9 marks]:**

a) In the context of semiconductor-metal interfaces, we consider field emission dominant if the characteristic energy of the semiconductor is over 5\(\times\) the thermal energy. For an interface with an effective mass of tunneling of 0.3\(m_e\), a semiconductor carrier density of \(n = 4.47\times10^{17}\), and a semiconductor relative permittivity of 11.7, determine the temperature below which field emission dominates. \(m_e\) is the rest mass of an electron. Give you answer in Kelvin.[3 marks]

b) Describe briefly the difference between conventional resistivity and specific interfacial resistivity.[2 marks]

c) An ultraviolet-visible (UVVis) spectroscopic absorption measurement is carried out on a semiconductor, and the material is observed to have an onset of absorption of 776 nm. An ultraviolet photoelectron spectroscopy (UPS) measurement is carried out on the same sample. During this UPS experiment, the longest-wavelength incident photons which result in photoelectron emission are 116 nm. At this wavelength of incident photons, electrons are emitted with a kinetic energy of 100 meV. The workfunction of the detector is 5.1V. Using this information, draw the band diagram of this semiconductor, labeling the conduction band minimum, the valence band maximum, and the band gap. Quote these energies in electron volts.[4 marks]

**Question 3 [8 marks]:**

a) We are designing a light-emitting transistor based on an ambipolar semiconductor. The TFT has a threshold voltage for electrons of \(V_{Te} = +5\) V and a threshold voltage for holes of \(V_{Th} = -7\) V. If you choose to apply a gate voltage of \(V_G = -40\) V, state what range of drain voltages would result in light emission.[3 marks]

b) A narrow-band-gap semiconductor is employed in two TFTs. In the first TFT, the electrodes only allow the injection and transport of holes. In the second TFT, both holes and electrons can be injected and transported. Use the parameters in the table below to determine the difference in measured source-drain current between the two TFTs, if one were to apply a gate and drain voltage of \(V_G = -20\) V and \(V_D = -10\) V, respectively. The temperature is 300K, and the channel length and width are \(L = 10\) \(\mu\)m, and \(W = 10\) mm respectively. You can assume the threshold voltage for holes and electrons are both zero, for both TFTs.[3 marks]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Electrons</th>
<th>Holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma) (A)</td>
<td>(3.45 \times 10^{-15})</td>
<td>(1.57 \times 10^{-15})</td>
</tr>
<tr>
<td>(T_0) (K)</td>
<td>460</td>
<td>600</td>
</tr>
</tbody>
</table>

c) When designing a light-emitting transistor, which architecture would be logical to choose? A bilayer TFT or a blend TFT? Explain why.[2 marks]
Question 4 [7 marks]:

a) The figure below shows the characteristics of two phototransistors: Phototransistor A and phototransistor B. Using these characteristics, decide which phototransistor is more likely to have its photocurrent enhancement due to the photoconductive effect and which is more likely to be due to the photovoltaic effect. Explain your answer. [2 marks]

b) A phototransistor, with a length of $L = 10 \, \mu m$, and width of $W = 1000 \, \mu m$ is held at constant gate and drain voltages and illuminated with pulsed green light. The figure below shows the optical power density applied to the phototransistor as a function of time (top), and the measured source-drain current of the phototransistor. From this data determine the external quantum efficiency of this device at these applied biases and illumination intensity. Give your answer in %. [3 marks]

c) Explain why it is possible to have a phototransistor with an external quantum efficiency above 100%. [2 marks]
Question 5 [7 marks]:

a) Conventionally we use positive voltages to represent logic signals (low = 0V and high = +5V for example). Draw a diagram for a complementary inverter (i.e. an inverter comprising of separate p-type and n-type transistors) that works with negative voltages (e.g. low = 0V and high = -5V) and a negative supply voltage. Explain why this device would operate as expected.[4 marks]

b) A complementary inverter is fabricated that has an infinite gain (i.e. perfectly sharp switching characteristics) at a switching voltage of $V_{in} = 3V$. If the inverter has the following voltage truth table, determine the low noise margin and high noise margin of this inverter. [3 marks]

<table>
<thead>
<tr>
<th>$V_{in}$</th>
<th>$V_{out}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0V to 3V</td>
<td>0.5V</td>
</tr>
<tr>
<td>3V to 5V</td>
<td>4V</td>
</tr>
</tbody>
</table>

Question 6 [6 marks]:

a) Describe two structural problems that can occur when depositing semiconductors onto substrates with different coefficients of thermal expansion, at elevated temperatures.[2 marks]

b) An organic semiconductor that has a Young’s Modulus of 1.5 GPa is deposited over the entire surface of a small flexible RFID tag, which has dimensions of 5cm × 5cm when not stretched. The semiconductor is known to crack when a stress is above 4.5 GPa is applied. What length could the RFID tag be stretched to in one direction before the semiconductor cracks? Give your answer in cm.[2 marks]

c) Describe a possible use of a thermoelectric in flexible electronics.[1 marks]

d) Provide a reason why you might want to use the compounds beta carotene in electronics.[1 mark]

Question 7 [5 marks]:

a) Briefly describe the operation of a chemiresistor.[1 mark]

b) State the difference between a water-gated TFT and an organic electrochemical transistor.[1 mark]

c) TFTs employing PEDOT:PSS as a channel material are called depletion-mode transistor. State what is meant by a depletion mode transistor.[1 mark]

d) Describe, with diagrams, how an ion pump would be used in the human body.[2 marks]