# PHAS0058 – Tutorial 4: Questions

**Question 1.** *(from 2021 and 2023 paper)*

A field-effect transistor (FET) incorporates a single layer of graphene as an active layer, and a ferroelectric material as an insulator.

a) Calculate the density of electrons in the graphene layer of the FET above after it has been cooled so that the insulator is in its ferroelectric phase. Assume that the relative dielectric constant ($\epsilon_r$) of the insulator in the ferroelectric phase is $\epsilon_r = 11$ (instead of $\epsilon_r$ = 5 in the paraelectric phase). The Fermi velocity is inversely proportional to the average dielectric constant of substrate, $\epsilon_{Sub}$, and air, $\epsilon_{Air}$ ($v_F \propto 1/\epsilon$, $\epsilon = (\epsilon_{Air} + \epsilon_{Sub})/2$). **[5]**

b) A gate voltage is applied to the FET and causes a shift of the optical absorption edge of the graphene layer of 0.2 eV.

i. Explain the origin of the shift (aka. Pauli blocking). **[2]**

ii. Calculate the total charge density in the graphene layer at temperatures above the ferroelectric transition, in the presence of the bias. **[3]**

**Question 2**. *(from 2022 paper)*

The free energy density of a hypothetical one-dimensional material is given by the equation:

$$\mathcal{F} = \beta \cdot (T - 373)P^2 + 20P^4 + \frac{1}{6}P^6 \quad (1)$$

Where $\beta$ is a constant, $P$ is the material's polarisation density, and $T$ is the material's absolute temperature (in Kelvin).

**i.** State if the expression above can be representative of a ferroelectric material and under which conditions. Justify your statement. **[4]**

ii. Draw a plot of $\mathcal{F}$ for the material described in (a) for $\beta = 1$ in SI units and $T = 363$ K. Also give the units of $\beta$ explicitly. **[3]**

iii. Explain the physical significance of $\beta$<0 and discuss the implications for the evolution of the state of order in the materials as a function of its temperature. **[3]**

iv. Give an expression of the free energy (density) for the same material as in (a) above under the application of an electric field oriented along the positive abscissae and with strength 4 MV/cm. Assume $\mathcal{F}$ is expressed in J/m$^3$ and $P$ in C/m$^2$. State if such a field strength is sufficient to induce a polarisation reversal in the material at a temperature $T = 372$ K. Justify your reasoning. (you can also still assume $\beta = 1$ in SI units) **[7]**

v. Calculate the minimum electric field strength needed for polarisation reversal in this material at T = 372 K and the temperature dependence of such a field for variations in the vicinity of the phase transition. **[3]**