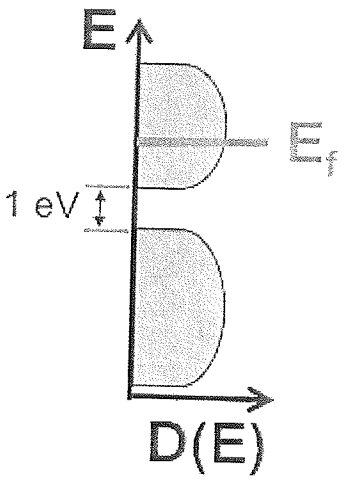
## Problem 1 (100 points)

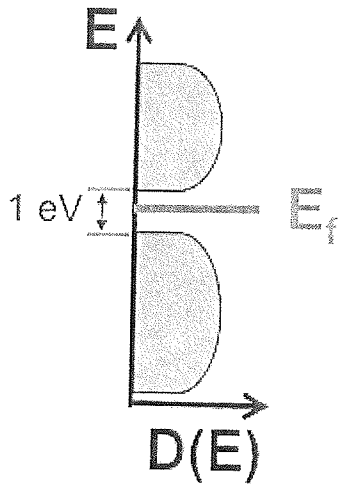
### Question A (40 points: 20+15+5)

(i) The density of states D(E) and the equilibrium Fermi energy $E_f$ for four materials are sketched below. Explain whether you would expect each of these to be a metal, a semiconductor, a semimetal or an insulator.

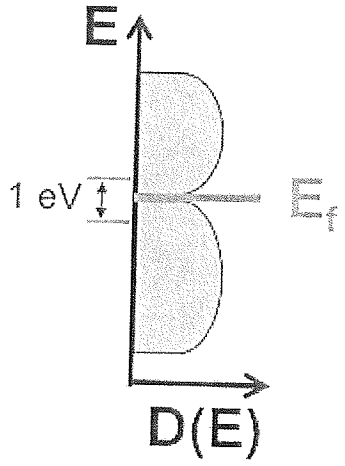
(a)



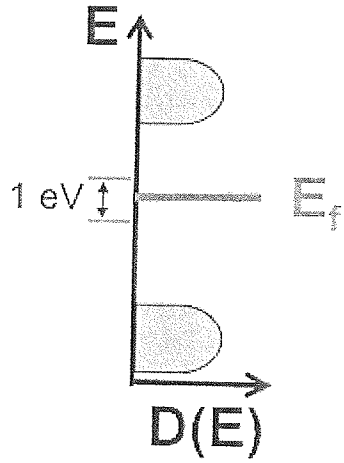

(b)




(c)




(d)




Write in Exam Book Only

(ii) Let us determine which of the following materials may be metals: Ge, C, Pb, Al, Ca, $Al_2O_3$, AgBr by something called an '*even electron rule*'.

A quick review of the periodic table shows that the number of electrons are: Ge(32), C(6), Pb (82), Al(13), Ca(20), O(8), Ag(47) , Br(35).

Using three facts: (a) each band can accommodate even number of electrons, (b) at T=0, all energy levels below $E_f$ are filled by electrons, and (c) the position of the $E_f$ with respect to the bands determines if the material is a metal or an insulator,

which of these materials would you definitely expect to be a metal?

(iii) Based on your answer in part (ii), can you explain in a single sentence what the '*even electron rule*' might be?

**PART B (60=12x5)**

A slab of Ge has been co-doped with P ( $10^{17}$ $cm^{-3}$) and Cu ( $10^{15}$ $cm^{-3}$). Experiments show that the minority carrier lifetime is $10^{-7}$ sec. Assume that $k_B T = 0.025$ eV. Assume that the following properties of Ge, Cu, and P are given:

- The bandgap of Ge is 0.66 eV, $N_C = 10^{19}$ $cm^{-3}$ and $N_V = 10^{20}$ $cm^{-3}$, and effective mass for both electrons and holes are $m = 0.5m_0$, where $m_0 = 9.1x10^{-31}$ kg.
- Cu has two energy levels: one 0.26eV below $E_C$, another 0.33eV eV below the $E_C$. And P has a single level 0.012 eV below $E_C$.

i) Calculate the position of the Fermi level with respect to the $E_C$. (ln 10=2.3)

ii) Which of the atoms are ionized and which ones are not? Explain.

iii) What is the thermal velocity of the minority carriers in this material? Approximate numbers are fine. Be careful about cm to meter conversion.

iv) What is the capture cross section for the minority carriers? Among P and Cu, who is responsible for the minority carrier recombination and why?

v) Can you determine the size of the atoms by assuming that the capture cross-section reflects the effective cross-section of the atoms to intercept electrons. Given that lattice constant for Ge is approximately 0.5 nm (with 8 atoms in a box) and Cu replaces one of the Si atom, does this number look reasonable?

Write in Exam Book Only