IMPERIAL COLLEGE LONDON

Final Copy

EE3-11
EE9AO8

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2011

MSc and EEE PART III/IV: MEng, BEng.and ACGI

ADVANCED ELECTRONIC DEVICES

Thursday, 19 May 10:00 am

Time allowed: 3:00 hours

There are FIVE questions on this paper.

Answer Question One and THREE other questions.

All questions carry equal marks.

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible	First Marker(s) :	K. Fobelets, K. Fobelets
	Second Marker(s) :	W.T. Pike, W.T. Pike

Special instructions for invigilators

Q1 is compulsory

Special instructions for students

Q1 is compulsory

Constants and Formulae

permittivity of free space:	$\varepsilon_o = 8.85 \times 10^{-12}$ F/m
permeability of free space:	$\mu_o = 4\pi \times 10^{-7}$ H/m
intrinsic carrier concentration in Si:	$n_{i\,Si} = 1.45 \times 10^{10}$ cm^{-3} at $T = 300$K
intrinsic carrier concentration in GaAs:	$n_{i\,GaAs} = 1.79 \times 10^{6}$ cm^{-3} at $T = 300$K
dielectric constant of SiO_2:	$\varepsilon_{ox} = 4$
dielectric constant of Si:	$\varepsilon_{Si} = 12$
electron affinity of Si	$\chi_{Si} = 4.05$ eV
electron affinity of GaAs	$\chi_{GaAs} = 4.07$ eV
electron affinity of InAs	$\chi_{InAs} = 4.9$ eV
electron affinity of AlAs	$\chi_{AlAs} = 3.58$ eV
effective density of states of Si:	$N_{C\,Si} = 2.8 \times 10^{19}$ cm^{-3} $N_{V\,Si} = 1.04 \times 10^{19}$ cm^{-3}
effective density of states of GaAs:	$N_{C\,GaAs} = 4.7 \times 10^{17}$ cm^{-3} $N_{V\,GaAs} = 9.0 \times 10^{18}$ cm^{-3}
thermal voltage:	$kT/e = 0.026$V at $T = 300$K
charge of an electron:	$e = 1.6 \times 10^{-19}$ C (1 eV)

$$p = N_v e^{(E_v - E_F)/kT} \text{ and } p_i = N_v e^{(E_v - E_i)/kT}$$

$$n = N_c e^{(E_F - E_c)/kT} \text{ and } n_i = N_c e^{(E_i - E_c)/kT}$$

Carrier density

$$I_{DS} = \frac{\mu C_{ox} W}{L}\left((V_{GS} - V_{th}) V_{DS} - \frac{V_{DS}^2}{2} \right)$$

MOSFET current

$$V_{th} = \phi_m - \phi_s + 2 \times \phi_F + \gamma \times \sqrt{2 \times \phi_F}$$

Threshold voltage

$$\phi_F = \frac{kT}{e} \ln\left(\frac{N_A}{n_i}\right)$$

Fermi potential (difference between intrinsic and Fermi level)

$$\gamma = \frac{\sqrt{2 e \varepsilon_s N_A}}{C_{ox}}$$

Body effect coefficient

$$J = \frac{e D_n n_p}{L_n}\left(e^{\frac{eV}{kT}} - 1\right) + \frac{e D_p p_n}{L_p}\left(e^{\frac{eV}{kT}} - 1\right)$$

Diode diffusion current density

$$V_0 = \frac{kT}{e} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Built-in voltage pn diode

$$W_{depl}(V) = \left[\frac{2\varepsilon (V_0 - V)}{e} \frac{N_A + N_D}{N_A N_D} \right]^{1/2}$$

Depletion width in pn diode

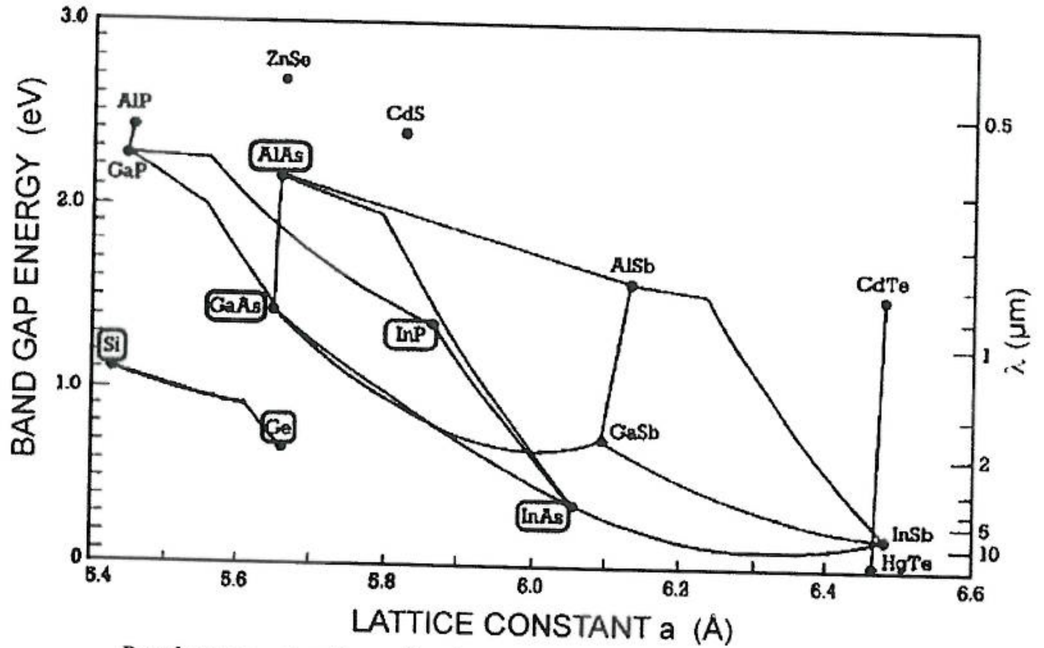
$$\frac{d^2 \Psi(x)}{dx^2} + \frac{2m}{\hbar^2}[V(x) - E]\Psi(x) = 0$$

1-D Schrödinger equation

$$S = \frac{dV_{GS}}{dLog(I_{DS})}$$

Sub-threshold slope

Figures with material parameters



Bandgap as a function of lattice constant for different semiconductors.

	E_G (eV)	χ (eV)	ε_r	μ_n (cm^2/Vs)	μ_p (cm^2/Vs)	a (nm)
Si	1.12	4.05	12	1450	450	0.542
Ge	0.66	4.0	16	3900	1900	0.565
GaAs	1.42	4.07	14	8500	400	0.564
AlAs	2.17	3.58	10	280	10	0.565

	ϕ (eV)
Al	4.08
Ni	5.01
Ti	4.33

Table 1: Left: Energy band gap E_G, electron affinity, χ, relative dielectric constant ε_r, electron μ_n and hole μ_p mobility and lattice constants a of different semiconductors. Right: Workfunction ϕ of different metals.

The Questions

1. Compulsory question.

a) Sketch the energy band diagram (E_c, E_v, E_F, E_G) from the gate to the substrate midway between source and drain of a p-channel enhancement mode MOSFET at threshold: $V_{GS} = V_{th}$ and $V_{DS} = 0V$. V_{th} is the threshold voltage.

[5]

b) Figure 1.1 gives a cross section of a MOSFET with the depletion region underneath the gate oxide and HDD (high doping density) areas. Redraw this sketch and clearly indicate the areas in which the charge is shared between the ohmic contacts and the gate.

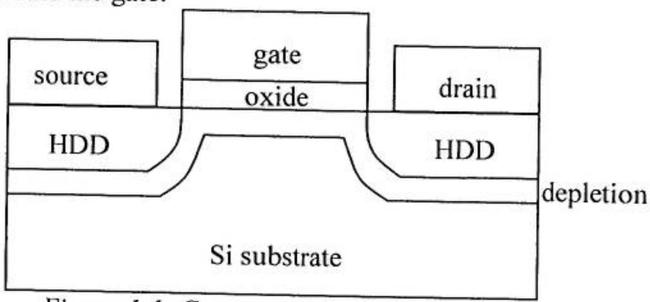


Figure 1.1: Cross section of a MOSFET.

[5]

c) Figure 1.2 gives a cross section of a JFET with a small negative gate voltage and small positive drain voltage (triode region) applied. Use Ohm's law to write a simple expression for the drain current I_{DS} as a function of the relevant geometrical parameters and the doping density in the channel region.

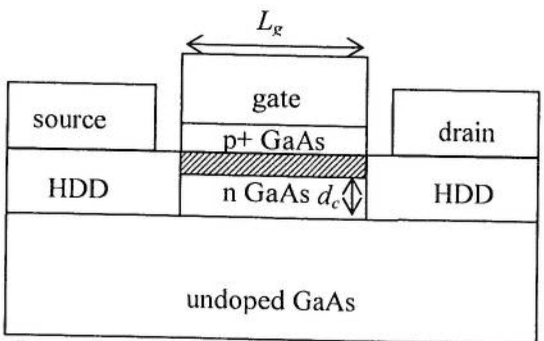


Figure 1.2: Cross section of a JFET with a gate length L_g, gate width W_g and undepleted channel depth d_c. The cross hatched area is depleted.

[5]

d) Sketch the energy band diagram of the GaAs/AlGaAs heterojunction in figure 1.3 (overleaf) upon contact (no bias applied). You can apply the rule:

$\Delta E_c = 60\% \ \Delta E_G$

$\Delta E_v = 40\% \ \Delta E_G$

The diagram should reflect the relative doping densities in the layers.

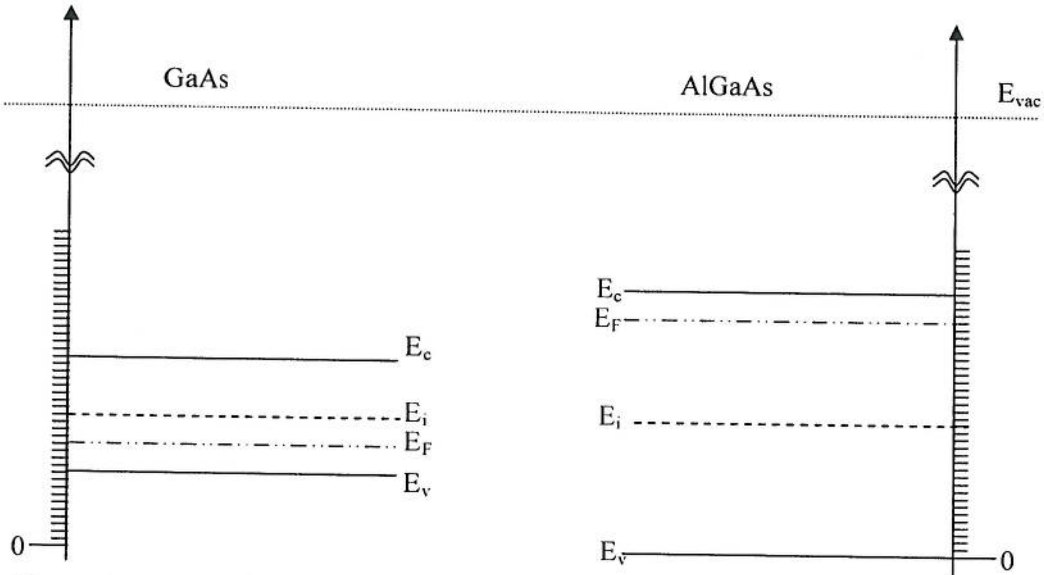


Figure 1.3: Sketch of the energy band diagram of GaAs and AlGaAs with respect to the vacuum level before contact. The bottom of the valence band of AlGaAs is taken to be zero.

[5]

2. The geometrical and doping parameters of a simple MOSFET are given in figure 2.1. The gate is in Aluminium with a workfunction $\phi_{Al} = 4.08$ eV. The temperature $T = 300$K.

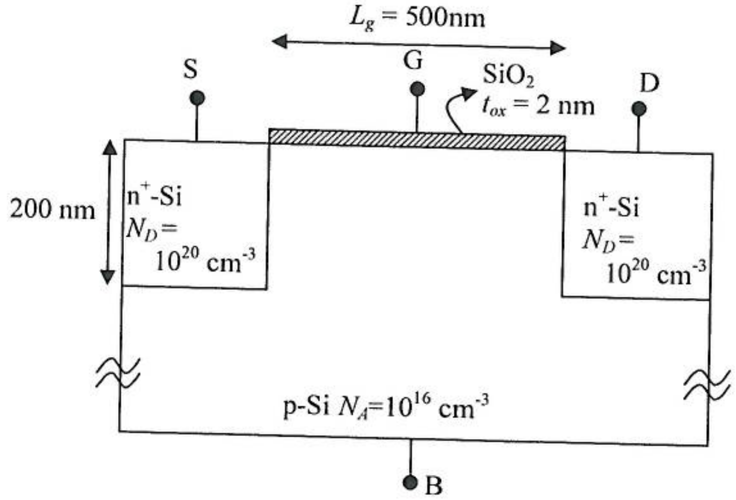


Figure 2.1: Cross section of a MOSFET. The gate width is $W_g = 1\ \mu m$. S, D, G, B is respectively source, drain, gate and bulk contact.

a) Calculate the threshold voltage V_{th} for the MOSFET given in figure 2.1 when no voltage is applied to the drain.

[4]

b) What is the value of the threshold voltage when the gate insulator is replaced by a high-k dielectric of the same thickness and a dielectric constant of $\varepsilon_{h\text{-}k} = 8$?

[4]

c) Give the ratio of the ON current in saturation for the Si oxide gated MOSFET over the high-k gated MOSFET for the same gate voltage V_{GS}=0.5V. You can ignore short channel effects.

[4]

d) Give the ratio of the sub-threshold slope S for the Si oxide gated MOSFET over the high-k gated MOSFET at their respective threshold voltages: $V_{GS} = V_{th}$. Remember that the sub-threshold slope can be derived from the MOS-bipolar equivalent in weak inversion. You can ignore any charge at the interface or in the insulator layer. You can assume that the maximum depletion width is of the order of 100 nm in both cases.

[4]

e) Is the influence of charge sharing on the threshold voltage in the high-k gated MOSFET higher or lower than in the SiO2-gated MOSFET? Prove your answer.

[4]

3.

a) Sketch a material cross section of a p-channel depletion mode Ge (germanium) MESFET (metal semiconductor field effect transistor) identifying the different areas, doping concentration (un, n^-, n, n^+, p^-, p or p^+) and type of contact.

[4]

b) Sketch the energy band diagram (E_c, E_v, E_F, E_G) from the gate contact to the bulk through the channel for a depletion mode p-channel Ge MESFET when $V_{GS} = V_{DS} = 0V$. Ensure that all relative distances between the energy levels are correct in all areas of the device.

[4]

c) Calculate the thickness of the channel layer that is necessary to obtain a p-channel Ge MESFET with a threshold voltage $V_{th} = 0V$ for $V_{DS} = 0V$. The doping density in the channel layer is 10^{16} cm^{-3}. The workfunction of the Ge channel is $\phi_{Ge} = 4.3$ eV and the workfunction of the gate contact is $\phi_G = 3.8$ eV. The dielectric constant of Ge is ε_{Ge}=16. You can neglect the influence of the interface states.

[4]

d) Design an integrated complementary MESFET structure (n and p type MESFET on one substrate) with the best performance per FET using the materials given in table 1 (see "Figures with material parameter" section in the beginning). You can use MBE techniques for material combinations and you can ignore Fermi level pinning. Explain your material choice briefly.

[4]

e) Explain the concept of surface states and their influence on the operation of MESFETs. Use energy band diagrams for your explanation.

[4]

4.

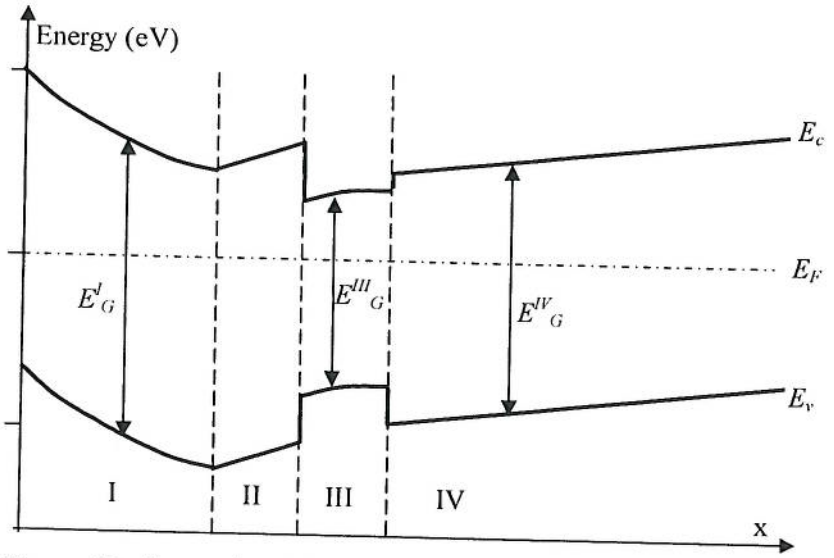


Figure 4.1: Energy band diagram (E_c, E_v, E_F, E_G) from the gate contact to the bulk through the channel of a device consisting of GaAs, $In_{0.8}Ga_{0.2}As$, and $Al_{0.4}Ga_{0.6}As$. Roman numbers indicate the different material regions. E^i_G is the bandgap in each region, i.

a)

i) Give the type of field effect transistor that is represented by the energy band diagram of figure 4.1.

ii) Which region is the channel and which type of majority carriers can be found in the channel?

[4]

b) Define the material and doping type in regions I, II, III, and IV.

[4]

c) Calculate the conduction band offset at the interface between region II and III and at the interface between region III and IV.

[4]

d) Sketch the material cross section of the device in figure 4.1 including all different contact, material and doping regions. Define and number each region 1, 2, 3, etc.

[4]

e) Write the part of the MEDICI input file that defines the material and doping density in the different regions of the device in d). The basic MEDICI commands necessary for this are given below. Q? is region number, MAT? is material (GAAs, ALGAAS, INGAAS), X? is mole fraction of the alloy, D? doping type (N or P), C? is concentration (magnitude should be appropriate, absolute value is not important). These values should be related to your answer in d).

```
1... MATERIAL REGION=Q? MAT?
2... MATERIAL REGION=Q? MAT? X.MOLE=X?
3... PROFILE REGION=Q? D?.TYPE CONC=C? UNIF
```

[4]

THIS PAGE IS INTENTIONALLY LEFT BLANK.

5. Below is a MEDICI TCAD input file for a device (line numbers are added).

```
1... TITLE  DEVICE

2... MESH

3... X.MESH x.min=0.000   x.max=0.140   h1=0.010
4... X.MESH x.min=0.140   x.max=1.260   h1=0.005
5... X.MESH x.min=1.260   x.max=1.400   h1=0.010

6... Y.MESH y.min=0.000  y.max=0.050  h1=0.001
7... Y.MESH y.min=0.050  y.max=0.240  h1=0.005
8... Y.MESH y.min=0.240  y.max=1.000  h1=0.010

9... REGION  num=1 x.min=0.0 x.max=1.400  y.min=0.000 y.max=0.010 s.oxide
10.. REGION  num=2 x.min=0.00 x.max=1.400  y.min=0.010 y.max=1.000 silicon

11.. ELECTR  name=source x.min=0.000 x.max=0.180 y.min=0.010 y.max=0.010
12.. ELECTR  name=drain  x.min=1.220 x.max=1.400 y.min=0.010 y.max=0.010
13.. ELECTR  name=gate  x.min=0.190  x.max=1.210 y.min=0.000 y.max=0.000
14.. ELECTR  name=back  x.min=0.000 x.max=1.400 y.min=1.000 y.max=1.000

15.. PROFILE  x.min=0.000 x.max=1.400 Y.MIN=0.010 Y.MAX=1.000
16.. +       P-TYPE  N.PEAK=5.e15  UNIFORM
17.. PROFILE  x.min=0.00 x.max=0.200 Y.MIN=0.010 Y.MAX=0.210
18.. +       N-TYPE  N.PEAK=1.e20  UNIFORM
19.. PROFILE  x.min=1.200 x.max=1.400 Y.MIN=0.010 Y.MAX=0.210
20.. +       N-TYPE  N.PEAK=1.e20  UNIFORM

22.. CONTACT  name=gate PRINT ALUMINUM

23.. SYMBOLIC GUMMEL CARRIERS=1  ELECTRON
24.. METHOD  ITLIMIT=20
25.. SOLVE   V(drain)=0.000  V(gate)=0.00  V(back)=0.00

26.. SYMBOLIC NEWTON  CARRIERS=1  ELECTRON
27.. MODELS analytic e.effect temperat=300. print
28.. SOLVE   V(drain)=0.0   V(gate)=0.00  V(back)=0.00

29.. SOLVE  ELEC=drain   VSTEP=0.1 NSTEP=10 PROJECT
30.. SOLVE  ELEC=gate    VSTEP=0.02 NSTEP=51 PROJECT

31.. LOG IVFILE=acdc0
32.. LOOP STEPS=100
33.. SOLVE ELEC=gate  VSTEP=-0.02  NSTEP=1  PROJECT
34.. L.END
```

Go to next page for questions on this input file

a) Sketch the material cross section of the device defined in the TCAD input file. Include the contacts, material and doping regions and the dimensions of each.

[4]

b) Sketch the data stored in the file acdc0 (line 31), given that the threshold voltage V_{th} = -0.2V and that saturation occurs at V_{DS} = 1V. Label axes and give the extreme values on the x-axis.

[4]

c) Based on the sketch in b) explain, using words and a graph, how you would be able to extract the threshold voltage from the characteristic in b).

[4]

d) How would the characteristic in b) change if the simulations would have been done with V(back) = -0.2V in line 28? Explain your answer briefly.

[4]

e) Propose two methods to change the design of the device such that the threshold voltage for V_{DS} = 1V becomes positive: V_{th} > 0. Explain why you think this method is valid and change the necessary lines in the input file to implement the change in the simulations.

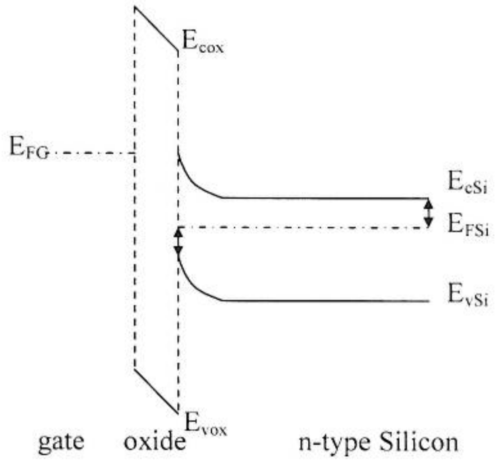
[4]

EE3-11
EE9 AO8

The Answers 2011

1. Compulsory question.

a)



[5]

b)

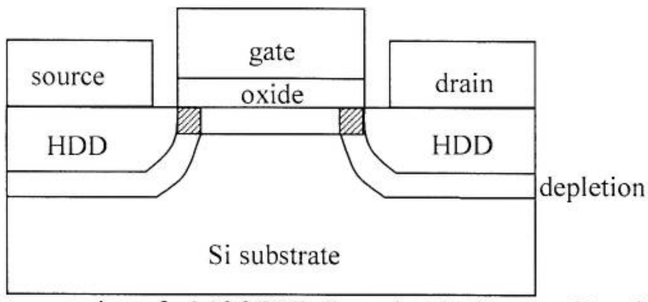


Figure 1: Cross section of a MOSFET. Cross-hatched areas of the depletion region are those where charge is shared.

[5]

c)

$$V = RI$$

$$dV(y) = I_{DS} dR(y)$$

$$dR = \frac{\rho dy}{A(y)}$$

$$dR = \frac{dy}{e\mu N_D W_g \left[d_c(y)\right]} = \frac{dy}{e\mu N_D W d_c}$$ Since in triode region the depletion depth is constant from source to drain. Thus d_c is constant.

$$I_{DS} = e\mu N_D W_g d_c \frac{dV(y)}{dy}$$

$$I_{DS} = e\mu N_D W_g d_c \frac{V_{DS}}{L_g}$$ Since in triode region the voltage drop across the gate length is linear.

[5]

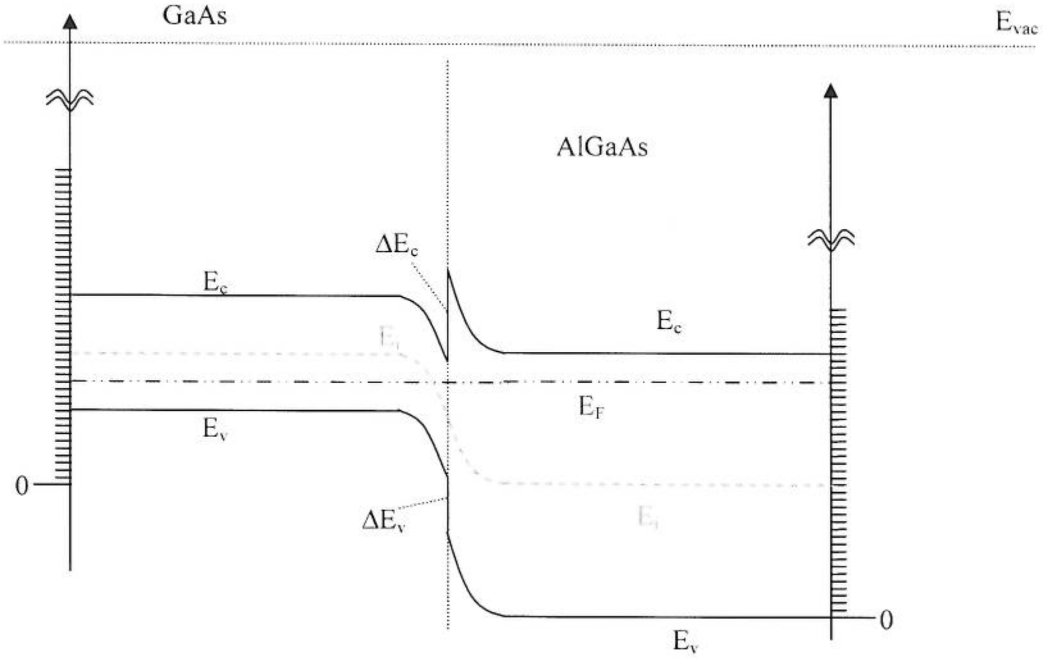
d) Doping density the same in both layers, thus band-bending approximately the same in both layers.

$E_{GAlGaAs}$ = 36 units

E_{GGaAs} = 16 units

ΔE_c = 0.6 (36-16) units = 12 units

ΔE_v = 0.4 (36-16) units = 8 units



[5]

2.

a) From formulae sheet:

$$V_{th} = \phi_m - \phi_s + 2\times\phi_F + \gamma\times\sqrt{2\times\phi_F}$$

$$\phi_F = \frac{kT}{e}\ln\left(\frac{N_A}{n_i}\right) = 0.026\ln\left(\frac{10^{16}}{1.45\times10^{10}}\right)\approx 0.35V$$

$$\gamma = \frac{\sqrt{2e\varepsilon_s N_A}}{C_{ox}} = \frac{t_{ox}\sqrt{2e\varepsilon_0\varepsilon_{Si}N_A}}{\varepsilon_{ox}\varepsilon_0} \quad \left(C_{ox} = \frac{\varepsilon_{ox}\varepsilon_0}{t_{ox}}\right)$$

$$\gamma = \frac{2\times10^{-7}\,cm\sqrt{2\times1.6\,10^{-19}\,C\times8.85\,10^{-14}\,\text{F/cm}\times12\times10^{16}}}{4\times8.85\,10^{-14}\,\text{F/cm}}\approx 0.033$$

Workfunction of the Si substrate:

$$\phi_{Si} = \chi_{Si} + {(E_c - E_F)}\big/_{e}$$

$$n_p = \frac{n_i^2}{N_A} = N_c e^{(E_F - E_c)/kT}$$

$$(E_c - E_F)\big/_{e} = kT\big/_{e}\ln\frac{N_A N_C}{n_i^2} = 0.026\ln\frac{10^{16}\times1.04\times10^{19}}{(1.45\times10^{10})^2} = 0.88V$$

$$\phi_{Si} = 4.05 + 0.88 = 4.93V$$

$$V_{th} = 4.08 - 4.93 + 2\times0.35 + 0.033\times\sqrt{2\times0.35} = -0.12V$$

Workfunction difference already creates a channel, thus depletion mode MOSFET.

[4]

b) The only parameter that changes in the equation is γ

$$\gamma = \frac{\sqrt{2e\varepsilon_s N_A}}{C_{in}} = \frac{t_{in}\sqrt{2e\varepsilon_0\varepsilon_{Si}N_A}}{\varepsilon_{in}\varepsilon_0}$$

Since the dielectric constant is increasing with a factor of 2 compared to SiO_2, γ decreases with a factor of 2.

$$V_{th} = 4.08 - 4.93 + 2\times0.35 + \frac{0.033}{2}\times\sqrt{2\times0.35} = -0.14V$$

[4]

c) From the formulae list: $I_{DS} = \frac{\mu C_{ox}W}{L}\left((V_{GS} - V_{th})V_{DS} - \frac{V_{DS}^2}{2}\right)$

In saturation the ON-current becomes (ignoring all short channel effects):

$$I_{DS} = \frac{\mu C_{ox}W}{L}(V_{GS} - V_{th})^2$$

$$\frac{I_{DS}^{ox}}{I_{DS}^{h-k}} = \frac{\frac{\mu C_{ox} W}{L}\left(V_{GS} - V_{th}^{ox}\right)^2}{\frac{\mu C_{h-k} W}{L}\left(V_{GS} - V_{th}^{h-k}\right)^2} = \frac{C_{ox}\left(V_{GS} - V_{th}^{ox}\right)^2}{C_{h-k}\left(V_{GS} - V_{th}^{h-k}\right)^2} = \frac{\varepsilon_{ox}\left(V_{GS} - V_{th}^{ox}\right)^2}{\varepsilon_{h-k}\left(V_{GS} - V_{th}^{h-k}\right)^2}$$

$$\frac{I_{DS}^{ox}}{I_{DS}^{h-k}} = \frac{4(0.5+0.12)^2}{8(0.5+0.14)^2} = 0.47$$

[4]

d) In a BJT the collector current is exponential of the form:

$$I_C = I_s \exp\left(\frac{eV_{EB}}{kT}\right)$$

In weak inversion, the current in the MOSFET is governed by diffusion like in a BJT, thus the weak inversion current in a MOSFET can be written as:

$I_{DS}^{WI} = I_o \exp\left(\frac{e(V_{GS} - V_{th})}{nkT}\right)$ with n determined by the voltage divider between the gate insulator capacitance and the depletion capacitance.

$$n = \frac{C_{in} + C_{depl}}{C_{in}} = 1 + \left(\frac{C_{depl}}{C_{in}}\right)$$

$$C_{depl} = \frac{\varepsilon_{Si}\varepsilon_o}{W_{depl}(\varepsilon_{Si}, \phi_F)} \quad \text{Independent of insulator}$$

$$n_{ox} = 1 + \left(\frac{C_{depl}}{C_{ox}}\right) = 1 + \left(\frac{t_{ox}\varepsilon_{Si}\varepsilon_o}{W_{depl}\varepsilon_{ox}\varepsilon_o}\right) \approx 1 + \left(\frac{2\times 12}{100\times 4}\right) = 1.06$$

$$n_{h-k} = 1 + \left(\frac{C_{depl}}{C_{h-k}}\right) = 1 + \left(\frac{t_{h-k}\varepsilon_{Si}\varepsilon_o}{W_{depl}\varepsilon_{k-k}\varepsilon_o}\right) \approx 1 + \left(\frac{2\times 12}{100\times 8}\right) = 1.03$$

Can now already claim that the sub-threshold slope in both cases will be nearly identical since n is nearly the same and thus the weak inversion current variation too.

But if calculations are done:

$$S = \left(\frac{dLog(I_{DS})}{dV_{GS}}\right)^{-1} = \left(\frac{dLog(I_o \exp\left(\frac{e(V_{GS} - V_{th})}{nkT}\right))}{dV_{GS}}\right)^{-1}$$

$$S = \left(\frac{d\left(\ln(I_o) + \left(\frac{e(V_{GS} - V_{th})}{nkT}\right)\right)}{\ln 10 \times dV_{GS}}\right)^{-1} = \left(\frac{\left(\frac{e}{nkT}\right)}{\ln 10}\right)^{-1} = \frac{nkT}{e}\ln 10$$

$$\frac{S_{ox}}{S_{h-k}} = \frac{n_{ox}}{n_{h-k}} = \frac{1.06}{1.03} = 1.029 \approx 1$$ [4]

e) the threshold voltage shift due to charge sharing is expressed by:

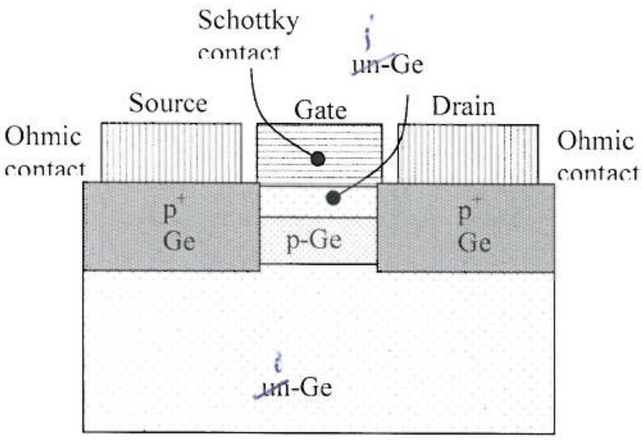
$$\Delta V_{th} = \frac{\Delta Q_{depl}}{C_{in}} = \frac{t_{in} \times \Delta Q_{depl}}{\varepsilon_o \varepsilon_{in}}$$

Since no change in ΔQ_{depl} the only influence is the dielectric constant of the insulator. Since $\varepsilon_{h\text{-}k} > \varepsilon_{ox}$, ΔV_{th} will be smaller for the high-k dielectric FET.

[4]

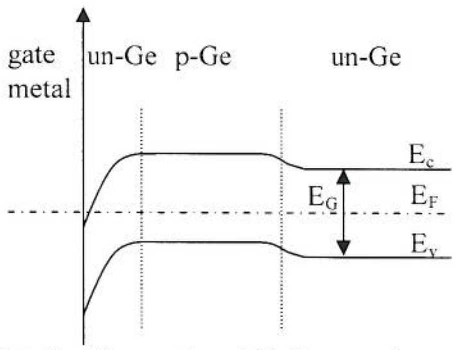
3.

a) .



[4]

b)



Note that the un-doped Ge layer underneath the gate metal is completely depleted by the Schottky contact depletion.

[4]

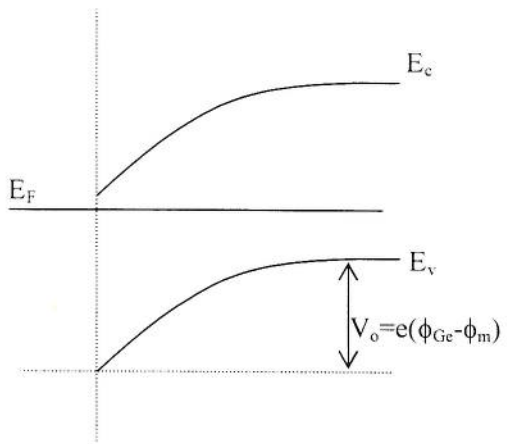
c) For $V_{DS} = 0V$ the depletion depth from gate into channel is homogeneous. The threshold voltage V_{th} is the gate voltage V_{GS} that we need to apply to deplete the channel completely. From the formulae sheet we have the expression for depletion width in a pn diode:

$$W_{depl}(V) = \left[\frac{2\varepsilon(V_0 - V)}{e} \frac{N_A + N_D}{N_A N_D} \right]^{1/2}$$

For the MESFET we have a one-side junction with $N_D >> N_A$. Then the depletion width becomes:

$$W_{depl}(V) = \left[\frac{2\varepsilon(V_0 - V)}{eN_A} \right]^{1/2}$$

V_o is the build-in voltage. For a Schottky contact this can be derived from the energy band diagram:



$$W_{depl}(V_{GS}) = \left[\frac{2\varepsilon(V_0 - V_{GS})}{eN_A}\right]^{1/2}$$

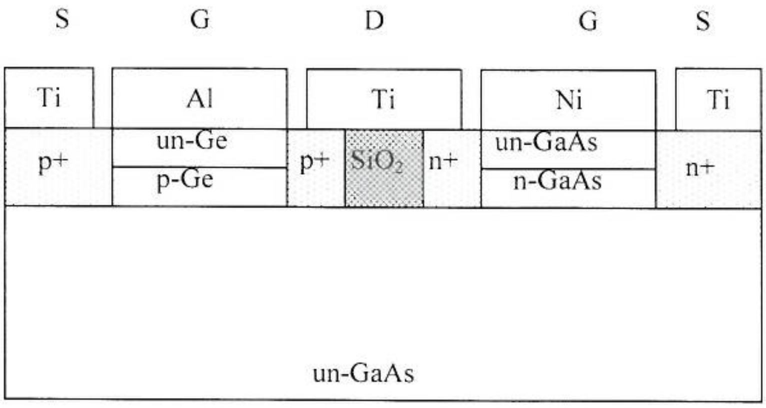
When $V_{GS}=V_{th}=0$ then $W_{depl}(V_{th}) = a_m = \left[\frac{2\varepsilon(V_0 - V_{th})}{eN_A}\right]^{1/2}$ thus

$$a_m = \left[\frac{2\varepsilon(V_0)}{eN_A}\right]^{1/2} = \left[\frac{2\varepsilon(\phi_{Ge} - \phi_m)}{eN_A}\right]^{1/2} = \left[\frac{2\times 16\times 8.85\,10^{-14}\,F/cm\times(4.3-3.8)}{1.6\,10^{-19}\times 10^{16}}\right]^{1/2}$$

$$a_m = 9.4\,10^{-5}\;cm = 9.4\,10^{-7}\;m$$

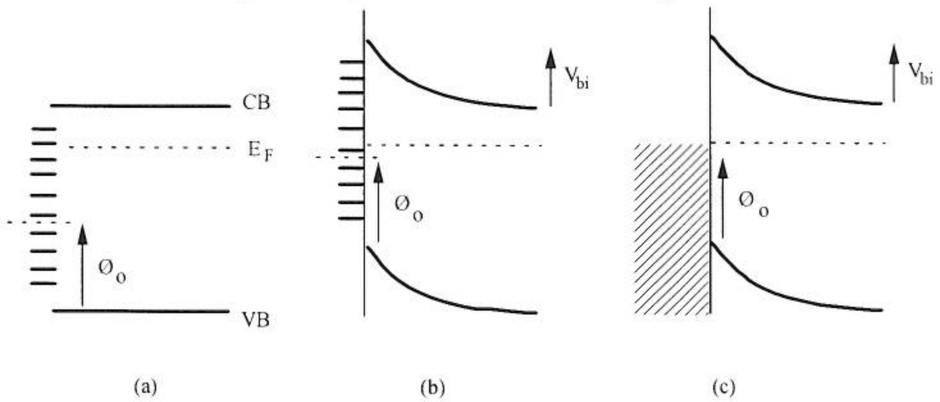
[4]

d) Ge is used for the p-FET since it has the highest hole mobility.
GaAs is used for the n-FET because of its high electron mobility.
The lattice constants of Ge and GaAs are the same so they can probably be grown on each other.
GaAs is chosen as the substrate since it is most resistive (larger bandgap).
Al is used for the Schottky contact on Ge because $\phi_{Al} < \phi_{p\text{-}Ge}$
Ni is used for the Schottky contact on GaAs because $\phi_{Ni} > \phi_{n\text{-}GaAs}$
Ti is used as ohmic contact for both as ϕ_{Ni} is approximately midgap for both material and thus compatible for an ohmic contact on heavily doped layers.
SiO_2 is used as insulation.



[4]

e) At the surface the covalent bonds are broken and contain only one electron. These dangling bonds give rise to surface states with energy levels distributed across the band gap of the semiconductor but localised at the surface. The surface states are characterised by their *neutral level* $\O_0$ that is equivalent to the Fermi energy of the surface.



(a) Surface states at the flat band condition and (b) after attaining equilibrium.
(c) In the presence of a metal the barrier height is unchanged

a) is a non-equilibrium situation: electrons from the bulk diffuse into the empty surface states creating an internal electric field (band bending away from E_F). b) In $\O_0$ and E_F are almost aligned and we have a potential barrier. c) When a metal is evaporated onto the surface, charge will again have to flow to equalise the Fermi energies but now the necessary charge can come from the surface states rather than from the bulk of the semiconductor. The depletion depth is almost unaffected and the barrier height is given by $\O_b = E_g - \O_0$. This is independent of the metal but depends on surface states at the metal-semiconductor junction. [4]

4.

a)

i) High electron mobility transistor (HEMT).

ii) region II, electrons

[4]

b) region I: n-$Al_{0.4}Ga_{0.6}As$ medium doping density
region II: n-$Al_{0.4}Ga_{0.6}As$ undoped
region III: un-$In_{0.8}Ga_{0.2}As$ undoped
region IV: n-GaAs medium doping

[4]

c) Use the electron affinity rule:

At II/III interface: $\chi_{II}+\Delta E_{c1}-\chi_{III} = 0$

At III/IV interface: $\chi_{III}-\Delta E_{c2}-\chi_{IV} = 0$

Calculate values of alloys (electron affinities in constants list):

χ $Al_{0.4}Ga_{0.6}As = 0.4 \times \chi$ AlAs $+ 0.6 \times \chi$ GaAs $= 0.4 \times 3.58 + 0.6 \times 4.07 = 3.87$ eV

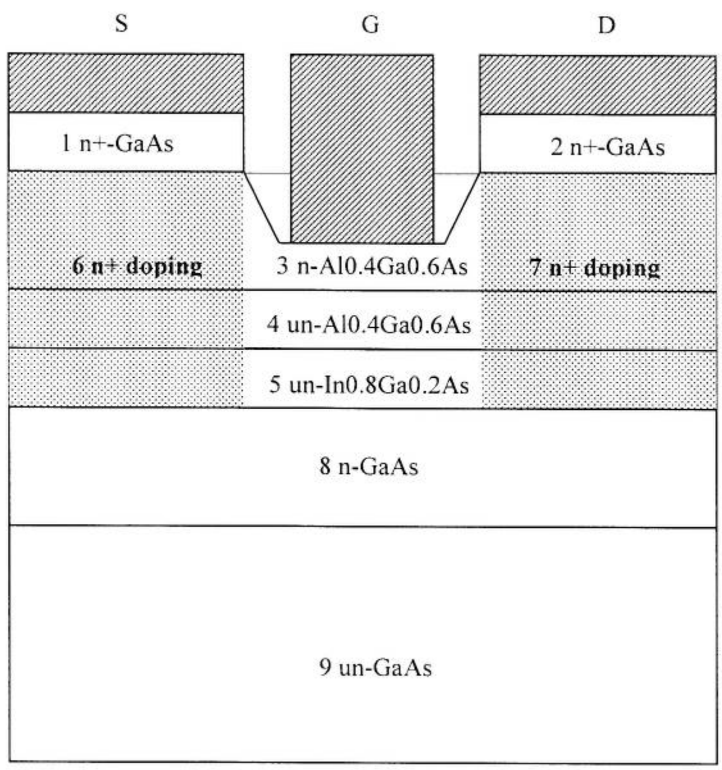
χ $In_{0.8}Ga_{0.2}As = 0.8 \times \chi$ InAs $+ 0.2 \times \chi$ GaAs $= 0.8 \times 4.9 + 0.2 \times 4.07 = 4.73$ eV

At II/III interface: $\Delta E_{c1} = \chi_{III} - \chi_{II} = 4.73$ eV - 3.87eV = 0.86 eV

At III/IV interface: $\chi_{III} - \chi_{IV} = \Delta E_{c2} = 4.73$ eV - 4.07 eV = 0.66 eV

[4]

d)



[4]

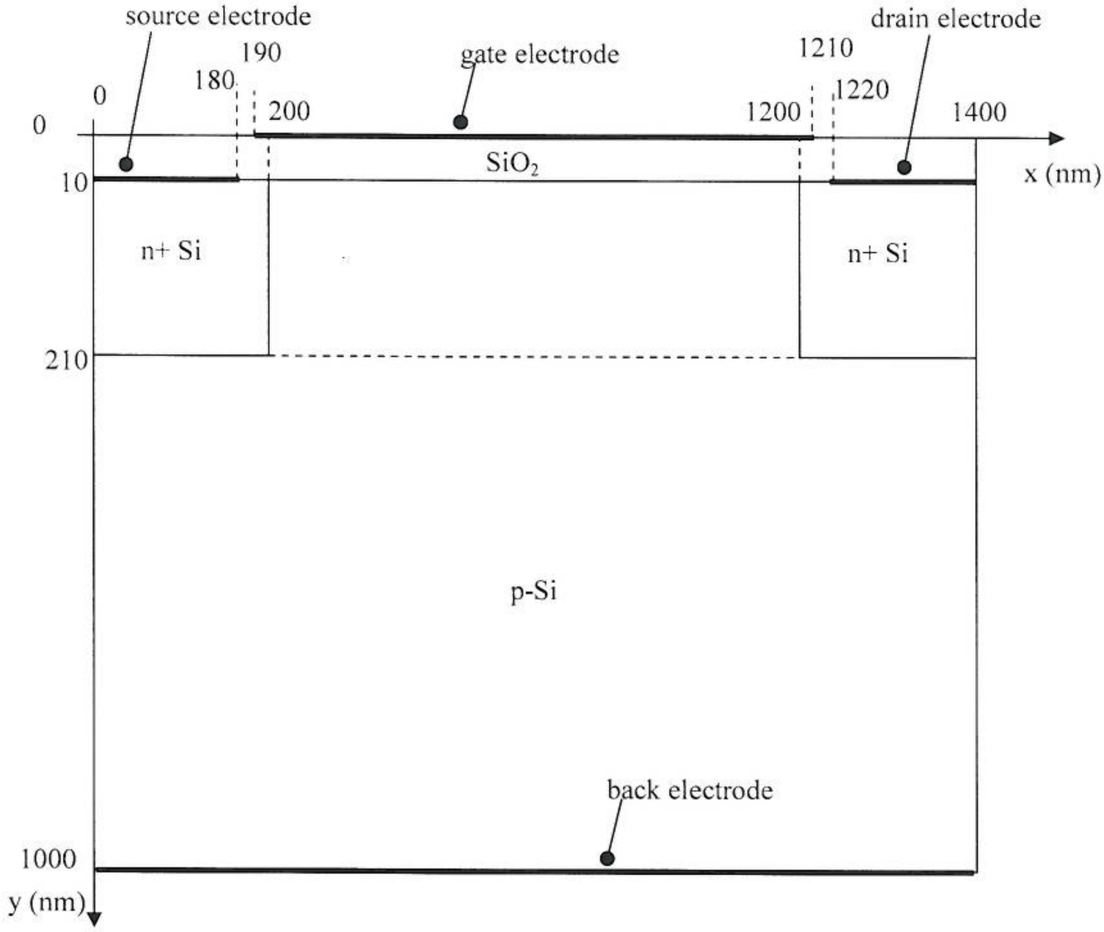
e)

```
MATERIAL REGION=1 GaAs
MATERIAL REGION=2 GaAs
MATERIAL REGION=3 AlGaAs X.MOLE=0.4
MATERIAL REGION=4 AlGaAs X.MOLE=0.4
MATERIAL REGION=5 InGaAs X.MOLE=0.8
MATERIAL REGION=8 GaAs
MATERIAL REGION=9 GaAs
PROFILE  REGION=1 N.TYPE CONC=1e20 UNIF
PROFILE  REGION=2 N.TYPE CONC=1e20 UNIF
PROFILE  REGION=3 N.TYPE CONC=1e18 UNIF
PROFILE  REGION=6 N.TYPE CONC=1e20 UNIF
PROFILE  REGION=7 N.TYPE CONC=1e20 UNIF
PROFILE  REGION=8 N.TYPE CONC=1e16 UNIF
```

[4]

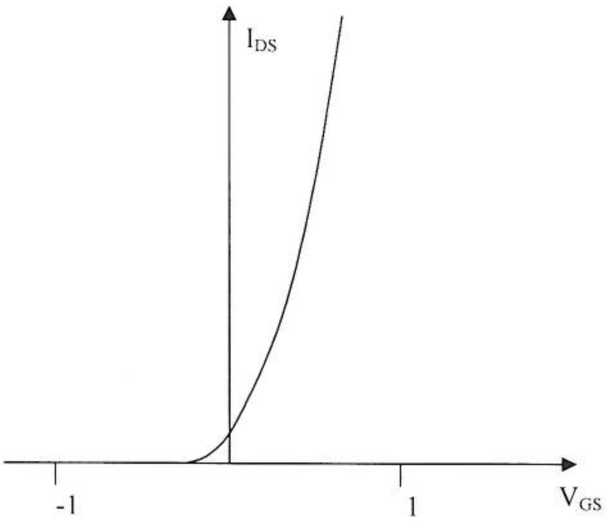
5.

a) Note: dashed lines are guide to the eye only.



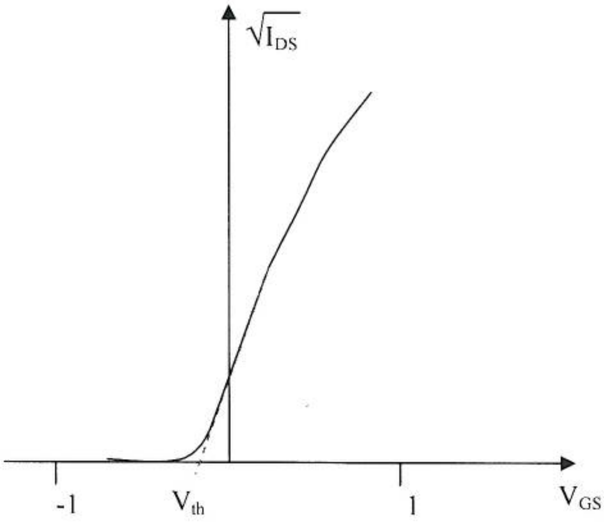
[4]

b) The stored data is the transfer characteristic. With the given voltages, the characteristic is in the saturation region and thus must look quadratic.



[4]

c) Since the transfer characteristic is in the saturation region, the sqrt of IDS has to be plotted. Some part of $\sqrt{I_{DS}}$ will be linear. The linear part is extended (tangential) to the gate voltage axis. The cross point between the tangential (red dotted line) and the V_{GS} axis is the V_{th}.



[4]

d) If a negative voltage is applied to the back contact then the substrate will be reverse biased (p-type). As a consequence the depletion region will grow and a larger gate voltage will need to be applied to invert the channel. Thus the threshold voltage becomes more positive and the I_{DS}-V_{GS} curve shifts to the right (in the + V_{GS} direction)

[4]

e) 2 of the following three can be chosen

1. Increase the doping density in the substrate. When the doping density in the substrate increases, it takes voltage on the gate to create and inversion layer with a carrier density the same as in the bulk. (see definition of V_{th} with energy band diagram).

Change line 15 and 16 to:
PROFILE x.min=0.000 x.max=1.400 Y.MIN=0.010 Y.MAX=1.000
+ P-TYPE N.PEAK=5.e17 UNIFORM

2. Increase the thickness of the oxide. When the oxide thickness increases, then a larger part of the gate voltage will drop across the oxide and thus more voltage is needed to obtain $V_s=2\phi_F$ across the semiconductor. $V_{GS}=V_{ox}+V_s$.

Change line 9 and as a consequence lines 10, 11 and 12 need to be changed16 to:
REGION num=1 x.min=0.00 x.max=1.400 y.min=0.000 y.max=0.100 s.oxide
REGION num=2 x.min=0.00 x.max=1.400 y.min=0.100 y.max=1.000 silicon

ELECTR name=source x.min=0.000 x.max=0.180 y.min=0.100 y.max=0.100
ELECTR name=drain x.min=1.220 x.max=1.400 y.min=0.100 y.max=0.100

3. Change the workfunction of the metal such that at $V_{GS}=0$ the workfunction difference between metal and p-Si is such that the SiO_2/Si interface depletes. Therefore we need to choose a gate metal (contact) with a larger workfunction than that of p-Si. $\phi_{metal} > \phi_{p\text{-}Si}$ the electrons will diffuse from Si to gate upon contact depletion the channel further from electrons (these are the inversion carrier type).

Change line 22 to (using data from table 1 in data hand out):
CONTACT name=gate PRINT TITANIUM

[4]