

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING  
EXAMINATIONS 2014-15

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

Corrected Copy

**ADVANCED ELECTRONIC DEVICES**

Monday, 8 December 9:00 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 |
|                       | Second Marker(s) : | S. Lucyszyn |



### **Special instructions for invigilators**

Q1 is compulsory

### **Special instructions for students**

Q1 is compulsory.

Do not use red nor green ink.

## Constants

permittivity of free space:  
 permeability of free space:  
 intrinsic carrier concentration in Si:  
 intrinsic carrier concentration in GaAs:  
 intrinsic carrier concentration in AlAs:  
 intrinsic carrier concentration in InAs:  
 dielectric constant of SiO<sub>2</sub>:  
 dielectric constant of Si:  
 dielectric constant of GaAs:  
 dielectric constant of AlAs:  
 dielectric constant of InAs:  
 electron affinity of Si  
 electron affinity of GaAs  
 electron affinity of AlAs  
 electron affinity of InAs  
 band gap of Si:  
 band gap of GaAs:  
 band gap of AlAs:  
 band gap of InAs:  
 effective density of states of Si:  
  
 effective density of states of GaAs:  
  
 effective density of states of AlAs:  
  
 effective density of states of InAs:  
  
 thermal voltage:  
 charge of an electron:

$\epsilon_0 = 8.85 \times 10^{-12}$  F/m  
 $\mu_0 = 4\pi \times 10^{-7}$  H/m  
 $n_{iSi} = 1.45 \times 10^{10}$  cm<sup>-3</sup> at  $T = 300$ K  
 $n_{iGaAs} = 1.79 \times 10^6$  cm<sup>-3</sup> at  $T = 300$ K  
 $n_{iAlAs} = 40$  cm<sup>-3</sup> at  $T = 300$ K  
 $n_{iInAs} = 1 \times 10^{15}$  cm<sup>-3</sup> at  $T = 300$ K  
 $\epsilon_{ox} = 4$   
 $\epsilon_{Si} = 12$   
 $\epsilon_{GaAs} = 13$   
 $\epsilon_{AlAs} = 10$   
 $\epsilon_{InAs} = 15$   
 $\chi_{Si} = 4.05$  eV  
 $\chi_{GaAs} = 4.1$  eV  
 $\chi_{AlAs} = 3.6$  eV  
 $\chi_{InAs} = 4.9$  eV  
 $E_{GSi} = 1.12$  eV  
 $E_{GGaAs} = 1.42$  eV  
 $E_{GAlAs} = 2.2$  eV  
 $E_{GInAs} = 0.36$  eV  
 $N_{CSi} = 2.8 \times 10^{19}$  cm<sup>-3</sup>  
 $N_{VSi} = 1.04 \times 10^{19}$  cm<sup>-3</sup>  
 $N_{CGaAs} = 4.7 \times 10^{17}$  cm<sup>-3</sup>  
 $N_{VGaAs} = 9.0 \times 10^{18}$  cm<sup>-3</sup>  
 $N_{CAlAs} = 1.5 \times 10^{19}$  cm<sup>-3</sup>  
 $N_{VAlAs} = 1.7 \times 10^{19}$  cm<sup>-3</sup>  
 $N_{CInAs} = 8.7 \times 10^{16}$  cm<sup>-3</sup>  
 $N_{VInAs} = 6.6 \times 10^{18}$  cm<sup>-3</sup>  
 $kT/e = 0.026$  V at  $T = 300$ K  
 $e = 1.6 \times 10^{-19}$  C (1 eV)

Table 0: Workfunction of metals

| metal | $\phi$ (eV) |
|-------|-------------|
| Al    | 4.08        |
| Ni    | 5.01        |
| Ti    | 4.33        |
| W     | 4.6         |

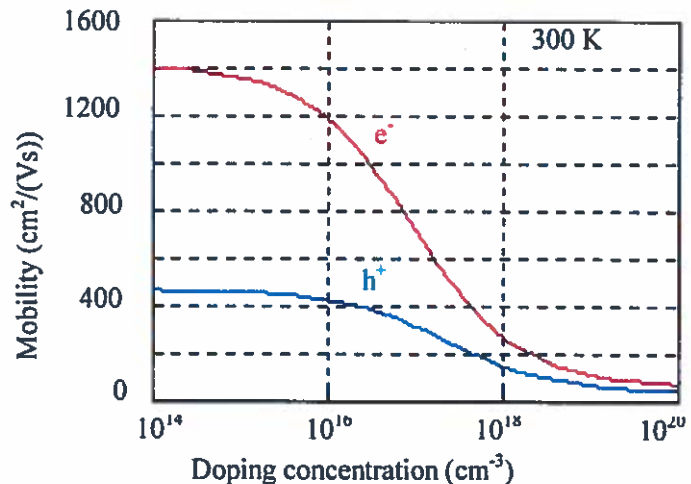


Figure 0: Electron and hole mobility in Si as a function of doping concentration.

## Formulae

$$p = N_v e^{(E_v - E_F)/kT}$$

$$n = N_c e^{(E_F - E_c)/kT}$$

$$J_n(x) = e\mu_n n(x)E(x) + eD_n \frac{dn(x)}{dx}$$

$$J_p(x) = e\mu_p p(x)E(x) - eD_p \frac{dp(x)}{dx}$$

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

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

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

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

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

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

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

$$S = \frac{dV_{GS}}{d\text{Log}(I_{DS})}$$

$$c = c_0 \exp\left(\frac{eV}{kT}\right) \text{ with } \begin{cases} c = p_n \text{ or } n_p \\ c_0 \text{ bulk minority carrier concentration} \end{cases}$$

$$\delta c = \Delta c \exp\left(\frac{-x}{L}\right) \text{ with } \begin{cases} \delta c = \delta p_n \text{ or } \delta n_p \\ \Delta c \text{ the excess carrier concentration at the edge of the depletion region} \end{cases}$$

$$L = \sqrt{D\tau}$$

$$D = \frac{kT}{e} \mu$$

Carrier density – Fermi-Dirac statistics

Drift – diffusion current density equations for electrons,  $J_n$  and holes,  $J_p$

Strong inversion MOSFET current

Threshold voltage

Fermi potential (difference between intrinsic and Fermi level)

Body effect coefficient

Diode current density

Built-in voltage pn diode

Depletion width in pn diode

Sub-threshold swing

Minority carrier injection under bias  $V$

Excess carrier concentration as a function of distance

Diffusion length

Einstein relation

1. Compulsory question.

a) For a p-type Si resistor.

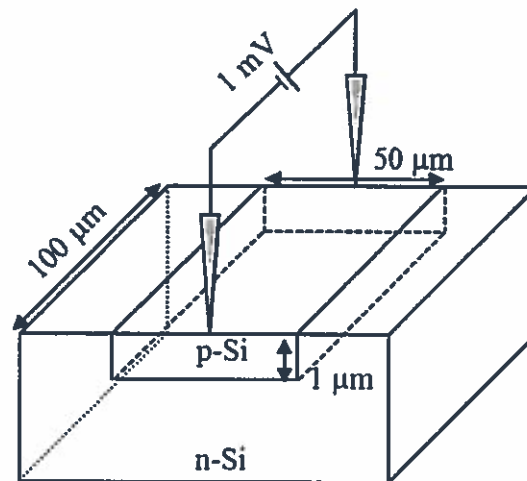


Figure 1.1: The geometry of a diffused p-type region in an n-Si substrate. The probe needles form Ohmic contacts and are shown as grey triangles.

In figure 1.1 a p-type volume has been defined within an n-Si substrate. The doping concentration of the substrate is  $N_D = 10^{14} \text{ cm}^{-3}$  and of the diffused layer is  $N_A = 10^{18} \text{ cm}^{-3}$ . Two Ohmic contacts are made at the edges of the diffused layer with probe needles.

- i) Calculate the current through this system when  $V = 1 \text{ mV}$  and the contacts have a resistance of  $1 \Omega$  each. [4]
- ii) Sketch the energy band diagram, including  $E_F$ ,  $E_C$ ,  $E_V$  and  $E_G$ , between the two contacts through the p-Si region when a voltage of  $1 \text{ mV}$  is applied. Include the influence of the contacts. Ensure all relative magnitudes in energy are correct. [5]

b) For a depletion mode n-channel GaAs MESFET

- i) Sketch the energy band diagram, including  $E_F$ ,  $E_C$ ,  $E_V$  and  $E_G$ , from the gate into the bulk when no bias voltages are applied. [4]
- ii) Calculate the value of the gate voltage that needs to be applied to fully deplete the channel when  $V_{DS} = V_{BS} = 0 \text{ V}$  and the metallurgic channel depth is,  $a_m = 200 \text{ nm}$ . The channel doping density is  $10^{17} \text{ cm}^{-3}$ . The gate metal is tungsten (W) and the gate surface is fully passivated. [5]

c) For a depletion mode AlGaAs/GaAs n-channel HEMT

- i) Sketch the energy band diagram, including  $E_F$ ,  $E_C$ ,  $E_V$  and  $E_G$ , from the gate into the bulk when no bias voltages are applied. [5]
- ii) Explain why the electron mobility in an n-HEMT is higher than in an n-MESFET. [2]

## 2. Velocity saturation in short channel Si MOSFETs.

The drift velocity-field relationship is given by:

$$|v_d| = |v_d^{\max}| \frac{\left(\frac{|E_x|}{|E_c|}\right)}{\left(1 + \frac{|E_x|}{|E_c|}\right)} \quad (1)$$

with  $v_d$  the drift velocity,  $v_d^{\max}$  the maximum velocity,  $E_x$  the electric field in the x direction and  $E_c$  the critical value of the electric field.

a) Plot the following:

i) The drift velocity-field curve for  $0 \leq E_x \leq 5 \times E_c$ . [2]

ii) Add the asymptotes in the low and high electric field region. [2]

iii) Derive an expression for  $E_c$  based on the asymptotes. [2]

b) Derive the source-drain current in the:

i) linear region. [8]

ii) saturation region. [3]

for the case velocity saturation occurs. The current can be expressed as:

$$I_{DS} = -W Q_I(x) |v_d(x)|. Q_I(x) \text{ is the inversion charge per area in strong inversion.}$$

Relate  $E_x$  to  $V_{CB}(x)$ , the potential difference between channel and bulk. All other short channel effects can be neglected in these derivations.

c) Plot the output characteristics,  $I_{DS}-V_{DS}$  for an nMOS for  $-V_{DD} < V_{DS} < V_{DD}$  with  $V_{DD} > V_{GS} - V_{th}$  and  $V_{GS} > V_{th}$ .

i) For a long channel nMOS that saturates at pinch-off. [3]

ii) For a short channel nMOS that saturates due to velocity saturation. [3]

iii) Give the relationship, ( $<$ ,  $>$ ,  $=$ ), between the saturation currents and voltages in i) and ii). [2]

3. *The use of SiGe in existing semiconductor device technology.*

- a) Sketch the energy band diagram ( $E_c$ ,  $E_v$ ,  $E_F$ ,  $E_G$ ) at zero bias of a completely unstrained n-Si – p-Si<sub>1-x</sub>Ge<sub>x</sub> diode. The material parameters are:  $N_D = 10^{13} \times N_A$ . The Si<sub>1-x</sub>Ge<sub>x</sub> is linearly graded from  $x_{Ge} = 0$  at the junction to  $x_{Ge} = 0.85$  at the end,  $L_{SiGe}$  of the SiGe layer. The length of the layers,  $L_{Si}$  and  $L_{SiGe}$  are longer than the minority carriers diffusion length. The bandgap of unstrained Si<sub>1-x</sub>Ge<sub>x</sub> is given by:  

$$E_G(x_{Ge}) = 1.12 - 0.41 \times x_{Ge}$$
The following relationship is valid for unstrained p-Si<sub>1-x</sub>Ge<sub>x</sub>:  

$$\chi(x_{Ge}) + E_G(x_{Ge}) = \text{constant for } 0 \leq x_{Ge} \leq 0.85, \text{ with } \chi(x_{Ge}) \text{ the Ge concentration dependent electron affinity.}$$
[10]
- b) Indicate the direction of the internal electric field on the sketch in a). [5]
- c) Derive the expression of the minority carrier current density in both the Si as well as the Si<sub>1-x</sub>Ge<sub>x</sub> region if a forward bias,  $V_a$  is applied across the diode in a). The mathematical expressions should be written as a function of material parameters:  $N_A$ ,  $N_D$ ,  $D_p$ ,  $D_n$ ,  $x$  and  $V_a$ . You should assume that  $V_a$  drops across the junction depletion region only. [10]



4. The influence of the access resistance in MOSFETs.

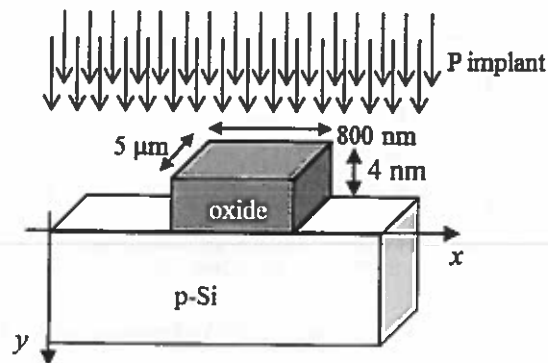


Figure 4.1: Source and drain doping self-aligned to the gate oxide. The dimension of the gate is given. Source and drain implants are symmetric.

After doping implantation and annealing, the junction depth is  $t_j$  and the diffusion in the lateral direction,  $x$  is  $t_j/4$  for both HDD and LDD.

For the HDD,  $N_D = 10^{20} \text{ cm}^{-3}$  and  $t_j = 400 \text{ nm}$ .

For the LDD,  $N_D = 10^{18} \text{ cm}^{-3}$  and  $t_j = 100 \text{ nm}$ .

In the bulk,  $N_A = 5 \cdot 10^{17} \text{ cm}^{-3}$ .

- a) Sketch the 2D ( $x$ - $y$ ) material cross section of the source implant of the MOSFET of figure 4.1 for two doping techniques (each followed by an anneal step).
  - i) Using HDD self-aligned to the gate oxide. [5]
  - ii) Using LDD and HDD with side wall spacer technology. The spacer width is 150 nm (in the  $x$  direction). [6]

Indicate the values of the transverse and lateral dimensions of the doping regions. The implanted volumes can be considered rectangular in all directions.

- b) Calculate the current,  $I_{DS}$  when  $V_{DS} = 0.1 \text{ V}$ ,  $V_{GS} = 1 \text{ V}$  and  $V_{th} = 0.4 \text{ V}$ . The influence of the depletion regions and short channel effects can be neglected. Hint: when expressions become complicated, substitute parameters by their numerical values.
  - i) For the self-aligned HDD implant with a total parasitic resistance,  $R_{tot} = 1.24 \Omega$ . [6]
  - ii) For the side wall spacer technique with LDD and HDD regions and a total parasitic resistance,  $R_{tot} = 24.68 \Omega$ . [6]
- c) Give two advantages of side wall spacer technology. [2]

5. *n-channel enhancement mode Si finFET.*

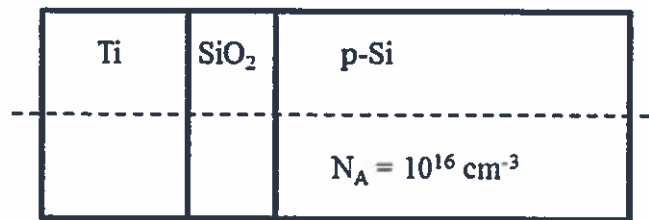


Figure 5.1: Heterojunction consisting of titanium, silicon dioxide and p-Si.

- a) Sketch the energy band diagram ( $E_c$ ,  $E_v$ ,  $E_F$ ,  $E_G$ ) of the heterojunction in figure 5.1 along the dashed line. [5]
- b) Calculate the depletion width into the p-Si layer in a) when no voltage is applied and  $1/5^{\text{th}}$  of the contact potential difference is dropped across the oxide layer. [5]
- c) Sketch a 3D tri-gate finFET on SOI without explicitly drawing the source and drain. Indicate where source and drain should occur with arrows only. The thickness of the oxide that wraps the fin underneath the Ti gate, is constant. The width, height and length of the fin are:  $H = 300$  nm,  $W = 200$  nm, and  $L = 400$  nm. [5]
- d) Sketch the energy band diagram ( $E_c$ ,  $E_v$ ,  $E_F$ ,  $E_G$ ) of this tri-gate finFET through the fin, perpendicular to the source-drain direction. No bias is applied. [5]
- e) Calculate the total current,  $I_{DS}$  through finFET of c) when a gate voltage is applied that creates inversion charge of  $Q_i = 5 \times 10^{-7}$  cm<sup>-2</sup>.  $V_{DS} = 1$  mV and no velocity saturation effects occur. The mobility in the channel reduces by a factor of 2 due to interface roughness scattering. You can ignore any edge effects. [5]