

Paper Number(s): **E3.11**  
**E4.42**  
**AS4**

IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE  
UNIVERSITY OF LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING  
EXAMINATIONS 2002

MSc and EEE PART III/IV: M.Eng., B.Eng. and ACGI

**ADVANCED ELECTRONIC DEVICES**

Tuesday, 7 May 10:00 am

There are FIVE questions on this paper.

Answer THREE questions.

**Corrected Copy**

Time allowed: 3:00 hours

**Examiners responsible:**

First Marker(s): Fobelets, K.

Second Marker(s): Juhasz, C.

Special instructions for invigilators:

None

Information for candidates:

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

$$W_n = \sqrt{\frac{2\epsilon_0 \epsilon_r}{e} (V_0 - V) \frac{N_A}{N_A N_D + N_D^2}}$$

$$W_p = \sqrt{\frac{2\epsilon_0 \epsilon_r}{e} (V_0 - V) \frac{N_D}{N_A N_D + N_A^2}}$$

$$n = N_C \exp\left[\frac{-(E_C - E_F)}{kT}\right]$$

$$p = N_V \exp\left[\frac{(E_V - E_F)}{kT}\right]$$

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

$$\frac{dE}{dz} = \frac{e}{\epsilon_0 \epsilon_r} (N_D + p - N_A - n)$$

Schottky contact current density :

$$J_{sch} = \frac{4\pi e m^* k^2 T^2}{h^3} \exp\left(\frac{-e\Phi_b}{kT}\right) \left[ \exp\left(\frac{eV}{kT}\right) - 1 \right]$$

pn diode current density :

$$J_{pn} = \left[ \frac{eD_n n_{p0}}{L_n} + \frac{eD_p p_{n0}}{L_p} \right] \left[ \exp\left(\frac{eV}{kT}\right) - 1 \right]$$

$$e = 1.602 \cdot 10^{-19} \text{ C}$$

$$h = 6.626 \cdot 10^{-34} \text{ Js}$$

$$n_i = 1.45 \cdot 10^{10} \text{ cm}^{-3} \text{ for Si at 300K}$$

$$n_i = 1.79 \cdot 10^6 \text{ cm}^{-3} \text{ for GaAs at 300K}$$

$$kT/q = 0.026 \text{ V at 300 K}$$

$$\epsilon_0 = 8.854 \cdot 10^{-12} \text{ F/m}$$

$$m_0 = 0.911 \cdot 10^{-30} \text{ kg}$$

$$N_{CSi} = 2.8 \cdot 10^{19} \text{ cm}^{-3}$$

$$N_{VSi} = 1.04 \cdot 10^{19} \text{ cm}^{-3}$$

$$N_{CGaAs} = 4.7 \cdot 10^{17} \text{ cm}^{-3}$$

$$N_{V GaAs} = 7 \cdot 10^{18} \text{ cm}^{-3}$$

$$\epsilon_r^{SiO_2} = 4$$

$$\epsilon_r^{Si} = 11.7$$

$$\epsilon_r^{GaAs} = 13.1$$

$$m_{nSi} = 0.19$$

$$m_{hSi} = 0.49$$

$$E_G = 1.42 \text{ eV for GaAs at 300K}$$

$$E_G = 2.18 \text{ eV for AlAs at 300K}$$

$$E_G = 1.12 \text{ eV for Si at 300K}$$

$$E_G = 0.66 \text{ eV for Ge at 300K}$$

Element	Work function $\Phi_m$ (V)
Au	5.1
W	4.55

Element	Electron affinity, $\chi$ (V)
Si	4.01
GaAs	4.07
AlAs	3.5

## 1. Heterojunctions

- i) Sketch the ideal energy-band diagram of the pn-heterojunction formed by p-GaAs – n-Al<sub>0.3</sub>Ga<sub>0.7</sub>As in thermal equilibrium and without external bias. Include  $E_c$ ,  $E_v$ ,  $E_f$ ,  $E_g$ ,  $\Delta E_c$  and  $\Delta E_v$ . Indicate the depletion width in the p ( $z_p$ ) and the n-doped ( $z_n$ ) regions. [8]
- ii) Is it possible to design a pn-homojunction with a non-symmetry in the conduction and valence band offset? Give a brief reason for your answer. [2]
- iii) Derive the expression for the depletion width in the n- and the p-doped region of the p-GaAs – n-Al<sub>0.3</sub>Ga<sub>0.7</sub>As heterojunction of part i). The Poisson equation is given on page 1. [10]

## 2. Gating JFET ↔ MESFET

The parameters of the ideal n-channel Si JFET and MESFET used in this question are:

**Si MESFET:** W as gate metal  
 $N_D = 10^{16} \text{ cm}^{-3}$ .

**Si JFET:**  $N_A = 10^{18} \text{ cm}^{-3}$ ,  $N_D = 10^{16} \text{ cm}^{-3}$ ,  
 $D_p = 10 \text{ cm}^2/\text{s}$ ,  $D_n = 25 \text{ cm}^2/\text{s}$ ,  
 $L_p = 10^{-3} \text{ cm}$ ,  $L_n = 1.5 \cdot 10^{-3} \text{ cm}$ .

All calculations to be carried out at  $T=300\text{K}$ .

- i) Calculate the built-in voltage  $V_{bi}$  for the a) JFET and b) MESFET. [5]
- ii) Compare the gate leakage current (reverse bias) of the MESFET gate to that of the JFET. [5]
- iii) Compare the turn-on voltage for a forward bias current density of  $10 \text{ A/cm}^2$  for both MESFET and JFET. [4]
- iv) Based on the results calculated in i), ii) and iii), answer the following questions:
- a) which FET has the highest input resistance in reverse bias and why? [2]
- b) which FET shows the highest switching speed? [2]
- c) sketch on the same graph the gate current - gate-source voltage characteristics for the JFET and MESFET. [2]

### 3. biCMOS

- i) Discuss briefly what is meant by biCMOS technology and why it is used in communication systems like mobile phones. [6]
- ii) In which device of biCMOS technology was SiGe introduced. Give at least two reasons for introducing SiGe and discuss the performance improvement it yields compared to a) GaAs technology and b) pure Si technology. [8]
- iii) Out diffusion of boron doping during the high thermal processing steps is a problem in SiGe biCMOS technology. Give two reasons why diffusion of boron doping degrades the performance of the device and give a way to minimise this out diffusion. [6]

### 4. FET ↔ HBT

- i) Draw the intrinsic small signal equivalent circuit of a FET for frequencies lower than 1 GHz and give the physical interpretation for each component. [5]
- ii) Draw the intrinsic hybrid  $\pi$  small signal equivalent circuit of a Bipolar Transistor (BT) for frequencies lower than 1 GHz and give the physical interpretation for each component. [5]
- iii) Derive the expression for the channel transit time  $\tau_t$  for a n-channel GaAs FET at low electric field and the base transit time  $\tau_b$  for a npn GaAs BT (no material gradients in the base). [5]
- iv) Calculate the cut-off frequency  $f_T$  of the FET and BT in iii) based on  $\tau_t$  and  $\tau_b$  respectively, at room temperature, and given the following parameters: [2]
- |             |  |            |  |
|-------------|--|------------|--|
| <b>FET:</b> | gate length $L_g = 0.5 \mu\text{m}$                  | <b>BT:</b> | base width $W_b = 0.5 \mu\text{m}$                           |
|             | gate width $W_g = 50 \mu\text{m}$                    |            | base collector depletion width $W_{bc} = 2 \mu\text{m}$      |
|             | $e^-$ mobility $\mu_n = 2000 \text{ cm}^2/\text{Vs}$ |            | electron diffusion constant $D_n = 52 \text{ cm}^2/\text{s}$ |
|             | $h^+$ mobility $\mu_p = 500 \text{ cm}^2/\text{Vs}$  |            | hole diffusion constant $D_p = 13 \text{ cm}^2/\text{s}$     |
|             | electric field $E = 1000 \text{ V/cm}$               |            | $V_{BE} = 0.6\text{V}$                                       |
- v) Explain briefly why the cut-off frequency calculated in iv) for both the FET and BT is too high compared to the performance of real devices. [3]

## 5. General questions

- a) Given the conduction band diagram of a GaAs HEMT from gate to bulk (see figure 5.1), draw the density of states in the quantum well for this structure. [2]

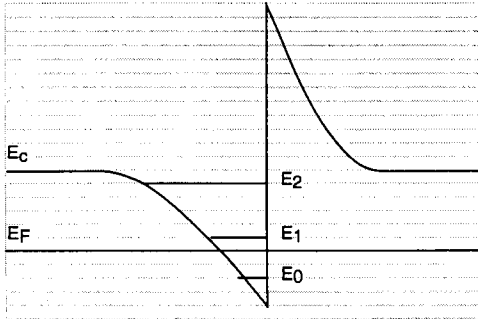


Figure 5.1: Conduction band diagram of HEMT.

- b) Why is the region immediately underneath the gate metal of a JFET highly doped? [2]
- c) Sketch the energy band diagram (include  $E_c$ ,  $E_v$ ,  $E_f$ ,  $E_g$ ) from gate to channel of a p-channel MESFET at  $V_{GS}=0V$ . Give the condition on the work function difference for good gate action. [2]
- d) Why is the mobility of the electrons in the channel of a GaAs/AlGaAs HEMT higher than in a GaAs MESFET with the same geometry and carrier density in the channel? [2]
- e) Emitter current crowding is important in power bipolar transistors. How can the un-homogeneous emitter current density be avoided by using processing techniques? [2]
- f) Why is the input noise current for a FET very small? [2]
- g) How can the base transit time in a Si/SiGe HBT be improved and give the reason for the improvement. [2]
- h) Can a Gunn diode be made in Si? Give the explanation for your answer. [2]
- i) Fig. 2 gives the current-voltage characteristics of a GaAs/AlGaAs resonant tunnelling diode. Sketch the energy band diagram corresponding to the bias points A, B and C of figure 5.2. [2]

Include  $E_c$ ,  $E_v$ ,  $E_f$ ,  $E_g$ ,  $\Delta E_c$  and  $\Delta E_v$

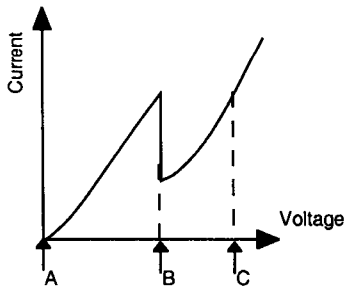


Figure 5.2: Current-voltage characteristics of RTD

- j) Give a reason for the use of biCMOS technology. [1]

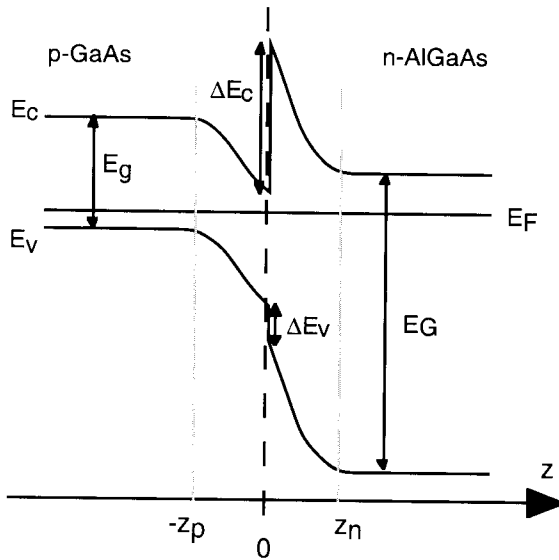
Question Number etc. in left margin

Mark allocation in right margin

**Q1 Heterojunctions**

i)

[8]



ii) no, since a difference in band gap of the two materials forming the junction is needed.

[2]

iii)

[10]

Poisson equation:  $\frac{dE}{dz} = \frac{e}{\epsilon_0 \epsilon_r} (p - n - N_A + N_D)$

$$\begin{cases} (1) \frac{dE}{dz} = 0 & z < -z_p \\ (2) \frac{dE}{dz} = \frac{-N_A e}{\epsilon_0 \epsilon_{GaAs}} & -z_p < z < 0 \\ (3) \frac{dE}{dz} = \frac{N_D e}{\epsilon_0 \epsilon_{AlGaAs}} & 0 < z < z_n \\ (4) \frac{dE}{dz} = 0 & z > z_n \end{cases}$$

$$E = -\frac{dV}{dz} \quad (5)$$

$$(5) \text{ in } (2): \frac{d^2V}{dz^2} = \frac{N_A e}{\epsilon_0 \epsilon_{GaAs}} \quad -z_p < z < 0$$

$$\text{Integrate: } \frac{dV}{dz} = \frac{N_A e}{\epsilon_0 \epsilon_{GaAs}} z + C_1$$

$$\text{@ } z = -z_p \quad \frac{dV}{dz} = 0 \Rightarrow C_1 = \frac{N_A e}{\epsilon_0 \epsilon_{GaAs}} z_p$$

$$\text{thus: } \frac{dV}{dz} = \frac{N_A e}{\epsilon_0 \epsilon_{GaAs}} (z + z_p)$$

$$\text{Integrate : } V = \frac{N_A e}{\epsilon_0 \epsilon_{GaAs}} (z + z_p)^2 + C_2$$

$$@ z = -z_p \quad V(-z_p) = V(-\infty) \quad (\text{continuity}) \Rightarrow C_2 = V(-\infty)$$

$$\text{thus solution : } V(z) = \frac{N_A e}{2\epsilon_0 \epsilon_{GaAs}} (z + z_p)^2 + V(-\infty) \quad -z_p < z < 0$$

$$(5) \text{ in (3) : } \frac{d^2 V}{dz^2} = \frac{-N_D e}{\epsilon_0 \epsilon_{AlGaAs}} \quad 0 < z < z_n$$

$$\text{identical to above : } V(z) = \frac{-N_D e}{2\epsilon_0 \epsilon_{AlGaAs}} (z - z_n)^2 + V(+\infty) \quad 0 < z < z_n$$

Continuity in  $z = 0$  :

$$1) \quad \epsilon_{GaAs} E(z \rightarrow -0) = \epsilon_{AlGaAs} E(z \rightarrow +0)$$

$$\text{gives : } \frac{N_A e}{\epsilon_0} z_p = \frac{N_D e}{\epsilon_0} z_n \quad \text{or} \quad N_A z_p = N_D z_n \quad (6)$$

$$2) \quad V(z \rightarrow -0) = V(z \rightarrow +0)$$

$$\text{gives : } \frac{N_A e}{2\epsilon_0 \epsilon_{GaAs}} (z_p)^2 + V(-\infty) = \frac{-N_D e}{2\epsilon_0 \epsilon_{AlGaAs}} (z_n)^2 + V(+\infty)$$

$$V_{bi} = V(+\infty) - V(-\infty) = \frac{N_A e}{2\epsilon_0 \epsilon_{GaAs}} (z_p)^2 + \frac{N_D e}{2\epsilon_0 \epsilon_{AlGaAs}} (z_n)^2 \quad (7)$$

$$(6) \rightarrow z_p^2 = \left( \frac{N_D}{N_A} z_n \right)^2$$

$$\text{in (7) : } V_{bi} = \frac{N_A e}{2\epsilon_0 \epsilon_{GaAs}} \left( \frac{N_D}{N_A} z_n \right)^2 + \frac{N_D e}{2\epsilon_0 \epsilon_{AlGaAs}} (z_n)^2$$

$$V_{bi} = \frac{e}{2\epsilon_0 \epsilon_{GaAs}} \frac{N_D^2}{N_A} (z_n)^2 + \frac{N_D e}{2\epsilon_0 \epsilon_{AlGaAs}} (z_n)^2 = \frac{e}{2\epsilon_0} \left( \frac{1}{N_A \epsilon_{GaAs}} + \frac{1}{N_D \epsilon_{AlGaAs}} \right) N_D^2 z_n^2$$

$$z_n = \sqrt{\frac{2V_{bi} N_A \epsilon_0 \epsilon_{GaAs} \epsilon_{AlGaAs}}{e N_D (N_A \epsilon_{GaAs} + N_D \epsilon_{AlGaAs})}}$$

$$(6) \rightarrow z_n^2 = \left( \frac{N_A}{N_D} z_p \right)^2$$

$$\text{in (7) : } V_{bi} = \frac{N_A e}{2\epsilon_0 \epsilon_{GaAs}} (z_p)^2 + \frac{N_D e}{2\epsilon_0 \epsilon_{AlGaAs}} \left( \frac{N_A}{N_D} z_p \right)^2$$

$$V_{bi} = \frac{e}{2\epsilon_0} \left( \frac{1}{N_A \epsilon_{GaAs}} + \frac{1}{N_D \epsilon_{AlGaAs}} \right) N_A^2 z_p^2$$

$$z_p = \sqrt{\frac{2V_{bi} N_D \epsilon_0 \epsilon_{GaAs} \epsilon_{AlGaAs}}{e N_A (N_A \epsilon_{GaAs} + N_D \epsilon_{AlGaAs})}}$$

$$W = z_p + z_n$$

## Q2 Gating JFET ↔ MESFET

i) a) JFET

[5]

pn-junctions control gating in JFETs, the built-in voltage  $V_{bi}$  expression is given in the formulae sheet.

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.026 \ln\left(\frac{10^{18} 10^{16}}{(1.45 \cdot 10^{10})^2}\right) = 0.819V$$

## b) MESFET

Schottky contact controls gating in MESFETs. The Schottky barrier and the doping density in the semiconductor determine the built-in voltage.

$$\text{Schottky barrier : } \phi_b = (\phi_m - \chi)$$

$$\text{Built-in voltage : } V_{bi} = \phi_b - \frac{(E_c - E_f)}{q}$$

$$\text{Maxwell-Boltzman : } n = N_c \exp\left[\frac{-(E_c - E_f)}{kT}\right] \Rightarrow -(E_c - E_f) = kT \ln\left(\frac{n}{N_c}\right)$$

$$V_{bi} = \phi_b + \frac{kT}{q} \ln\left(\frac{n}{N_c}\right) = 4.55 - 4.01 + 0.026 \ln\left(\frac{10^{16}}{2.8 \cdot 10^{19}}\right) = 0.334V$$

ii) The gate leakage currents are the reverse bias currents in the gate diodes.

[5]

See current density equations on formulae sheet.

The exponential term in both current expressions is negligible in reverse bias.

## a) JFET

$$J_{pn,rev} = -\left[\frac{eD_n n_{p_0}}{L_n} + \frac{eD_p p_{n_0}}{L_p}\right]$$

$$n_{p_0} = \frac{n_i^2}{p_{p_0}} = \frac{n_i^2}{N_A} = \frac{(1.45 \cdot 10^{10})^2}{10^{18}} = 2.103 \cdot 10^2 \text{ cm}^{-3} \quad \text{minority carrier expression}$$

$$p_{n_0} = \frac{n_i^2}{n_{n_0}} = \frac{n_i^2}{N_D} = \frac{(1.45 \cdot 10^{10})^2}{10^{16}} = 2.103 \cdot 10^4 \text{ cm}^{-3} \quad \text{minority carrier expression}$$

$$J_{pn,rev} = -\left[\frac{1.602 \cdot 10^{-19} \cdot 25 \cdot 2.103 \cdot 10^2}{1.5 \cdot 10^{-3}} + \frac{1.602 \cdot 10^{-19} \cdot 10 \cdot 2.103 \cdot 10^4}{10^{-3}}\right] = -(5.615 \cdot 10^{-13} + 3.369 \cdot 10^{-11}) = -3.425 \cdot 10^{-11} \text{ A/cm}^2$$

## b) MESFET

The gate leakage currents in MESFETs are much larger than the gate leakage currents in JFETs.

$$J_{sch,rev} = -\frac{4\pi e m^* k^2 T^2}{h^3} \exp\left(\frac{-e\Phi_b}{kT}\right) = -\frac{4\pi e^3 m^* (kT/e)^2}{h^3} \exp\left(\frac{-e\Phi_b}{kT}\right)$$

$$J_{sch,rev} = -\frac{4\pi (1.602 \cdot 10^{-19})^3 \cdot 0.19 \cdot 0.911 \cdot 10^{-30} \cdot (0.026)^2}{(6.626 \cdot 10^{-34})^3} \exp\left(-\frac{(4.55 - 4.01)}{0.026}\right)$$

$$J_{sch,rev} = -19.85 \text{ A/m}^2 = -19.85 \cdot 10^{-4} \text{ A/cm}^2$$

iii) The turn-on voltage is the voltage at which the gate starts conducting. This means that the  $-1$  term in the current expressions is negligible. (see reverse bias current values in ii)

[4]



JFET:

$$J_{pn} = J_{pn,rev} \left[ \exp\left(\frac{eV_{on}}{kT}\right) \right]$$

$$V_{on} = \frac{kT}{q} \ln\left(\frac{J_{pn}}{J_{pn,rev}}\right)$$

$$V_{on} = 0.026 \ln\left(\frac{10}{3.425 \cdot 10^{-11}}\right) = 0.686V$$

MESFET:

$$J_{sch} = J_{sch,rev} \left[ \exp\left(\frac{eV_{on}}{kT}\right) \right]$$

$$V_{on} = \frac{kT}{q} \ln\left(\frac{J_{sch}}{J_{sch,rev}}\right)$$

$$V_{on} = 0.026 \ln\left(\frac{10}{19.85 \cdot 10^{-4}}\right) = 0.22V$$

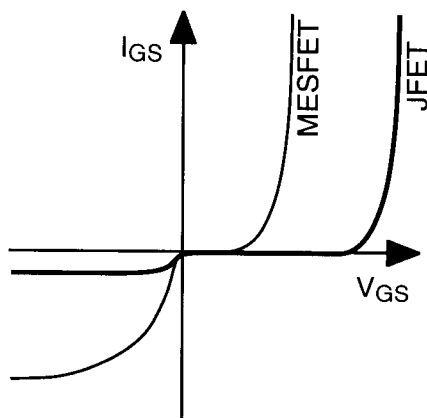
The turn-on voltage of the MESFET is lower than the turn-on voltage of the JFET.

iv) a) the JFET because the reverse bias current through the gate is lowest.

b) MESFET

c)

[6]



### Q3 biCMOS

Essential information is underlined.

i) biCMOS technology is a processing technology which allows to monolithically integrate bipolar transistors with Si CMOS. The reason for this integration in communication applications is the need for an integration of the digital and analogue part, the need for low power and low noise performance, and the need for compact portable circuits. The digital part is performed by Si CMOS which has low power and low noise characteristics. However the analogue part needs to operate at much higher frequencies, therefore bipolar transistors are more useful.

[6]

ii) SiGe was introduced in the base region of the bipolar transistor. The use of SiGe in the base of the bipolar transistor has several advantages.

a) Compared to GaAs technology

Currently GaAs is/was used for the rf analogue circuits, however the use of III-V materials inhibits an easy and cheap integration of the Si CMOS digital part with the analogue circuits. The noise performance of Si-based materials is better than that of III-V materials. The low frequency noise of SiGe HBTs is better than GaAs due to the existence of a native oxide for Si. The thermal conductivity of SiGe is better than that of GaAs important for power transistors.

b) Compared to Si technology

Introducing SiGe in the base of the bipolar transistor improves the emitter efficiency and the current gain of the transistor. This is due to the band gap difference which results in a valence band discontinuity which acts as a potential barrier for holes flowing from base to emitter. This reduces hole current, improving  $\gamma$ . The bandgap difference between base and emitter occurs in an exponential term in the current gain  $\beta$ . This gain improvement allows for an increased base doping (which decreases the emitter efficiency) generating a lower base resistance and thus higher operation frequency.

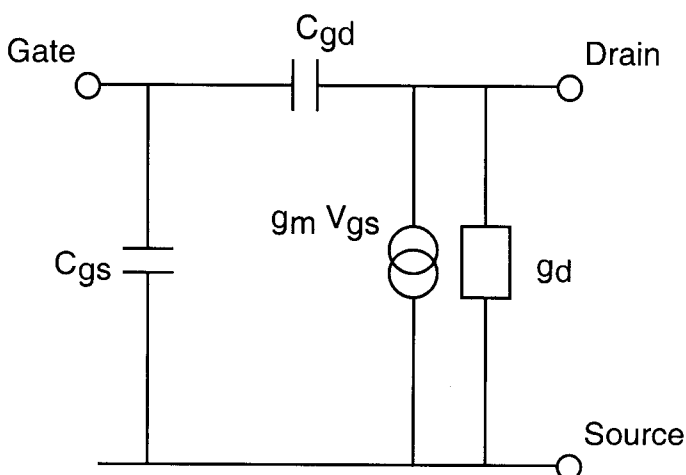
[8]

c) During the high thermal steps for e.g. anneal of doping implantation damage, boron doping in the base layer of the bipolar transistor diffuses into the emitter and collector region. This out-diffusion of p-type doing atoms increases the effective base width, which allows for more recombination current to occur in the base (degrades the emitter efficiency). More over in the case of a SiGe base, a part of the increased base which is Si will be at the emitter side and thus the barrier for hole current from the base to the emitter is not existent at that point which will reduce the gain of the transistor. The lack of Ge at the collector side of the HBTs in biCMOS technology (only the base is SiGe in SiGe biCMOS technology) introduces a barrier for the electrons which reduces the collector current and degrades the Early voltage of the device.

Small amounts of C are included in the base (SiGeC) region of the transistors and have shown reduced out diffusion of B atoms from the base.

[6]

#### Q4 FET $\leftrightarrow$ HBT



i)

[5]

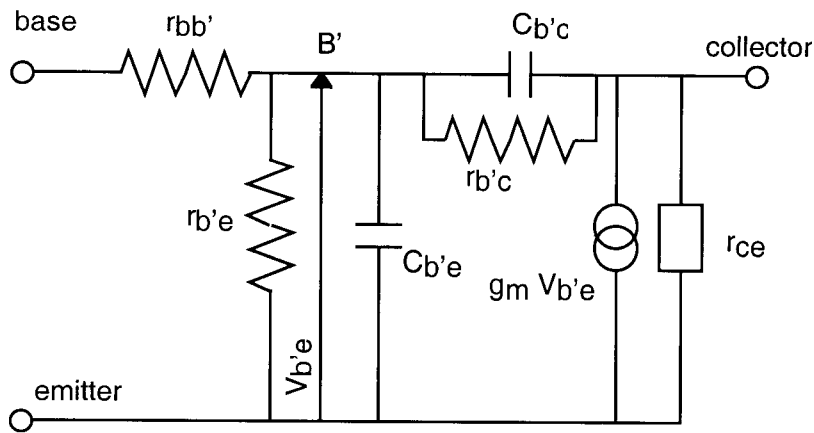
$C_{gd}$ : gate drain capacitance, is the variation of the charge under the gate as a function of the drain voltage

$C_{gs}$ : gate source capacitance, is the variation of the charge under the gate as a function of the source voltage

$g_m V_{gs}$ : current source, current through the channel controlled by the gate.  $g_m$  is the transconductance, is a measure for the control of the gate on the channel.

$g_d$ : output conductance, a finite output conductance is due to gate length

modulation.



- ii)
- $r_{bb'}$ : base spreading resistance, gives rise to a voltage drop due to emitter current crowding
  - $C_{b'e}$ : emitter-base junction capacitance (diffusion + depletion capacitance)
  - $r_{b'e}$ : emitter-base junction diffusion resistance
  - $C_{b'c}$ : collector-base junction capacitance (diffusion + depletion capacitance)
  - $r_{b'c}$ : collector-base junction diffusion resistance (large)

$g_m V_{gs}$ : current source, collector current dependent on the internal base-emitter voltage.  $r_{ce}$ : output resistance primarily due to the early effect. [5]

iii) n-channel FET [5]

$$\tau_t = L/v = L/\mu E$$

With L: channel length, m: mobility and E: electric field.

npn BT:

Charge in base of npn (electrons):

$$Q_b = \frac{en'_p W}{2} \quad (n'_p \ll n'_n)$$

$$Q_b = \frac{en_{p0} e^{\frac{eV_{be}}{kT}} W}{2}$$

Electron current injected into base from emitter:

$$I_e = \frac{eD_n n_{p0}}{W} e^{\frac{eV_{be}}{kT}}$$

$$e^{\frac{eV_{be}}{kT}} = \frac{I_e W}{eD_n n_{p0}}$$

into  $Q_b$

$$Q_b = \frac{en_{p0} I_e W^2}{2eD_n n_{p0}} = \frac{I_e W^2}{2D_n}$$

The base transit time is determined by the emitter-base diffusion capacitance:

$$C_{be, diff} = \frac{dQ_b}{dV_{be}}$$

$$C_{be, diff} = \frac{W^2}{2D_n} \frac{dI_e}{dV_{be}} = \frac{W^2}{2r_e D_n}$$

Hence the charging time becomes :

$$\tau_b = C_{be, diff} r_e = \frac{W^2}{2D_n}$$

iv) FET:  $f_T = 1/\tau_t = \mu E/L = 2000 \cdot 1000 / (0.5 \cdot 10^{-4}) = 4 \cdot 10^{10} \text{ Hz} = 40 \text{ GHz}$  [2]

BT:  $f_T = 1/\tau_b = 2 D_n / W^2 = 2 \cdot 52 / (0.5 \cdot 10^{-4})^2 = 4.16 \cdot 10^{10} \text{ Hz} = 41.6 \text{ GHz}$

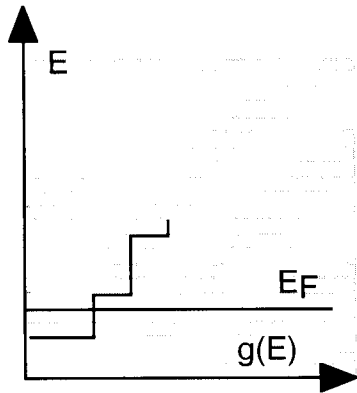
v) FET: the intrinsic and extrinsic capacitance and resistance values of the FET are ignored in the cut-off frequency calculation based on channel transit time.

BT: In the calculation of the cut-off frequency the complete emitter-collector delay has to be taken into account, meaning that in the calculations of iv) the collector depletion transit time, collector capacitance charging time, emitter capacitance charging time have been ignored. Further reductions in  $f_T$  will be due to external parasitics. [3]

**Q5 general questions**

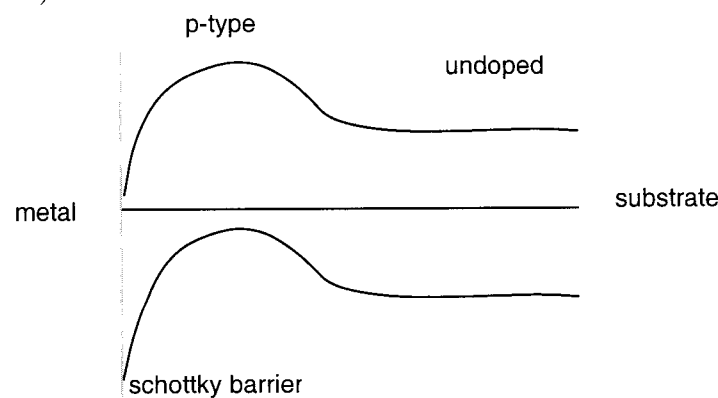
i)

[2]



ii) The gate needs to control the conduction in the channel, therefore the depletion variation caused by the gate should mainly happen in the channel region. When the region under the gate is highly doped and the channel lightly doped the depletion width will extend in the least doped area thus mainly in the channel. [2]

iii)



Condition on work function difference for good schottky barrier on p-type material is:

$$\phi_{\text{semiconductor}} > \phi_{\text{metal}}$$

(then transfer of electrons from the metal to the semiconductor will happen, making the semiconductor more n-type near junction and creating a barrier for holes)

[2]

iv) Because in HEMTs modulation doping is being used, which means that the doping layer is separated from the channel layer, reducing impurity scattering and thus increasing the mobility of the carriers in the undoped channel. [2]

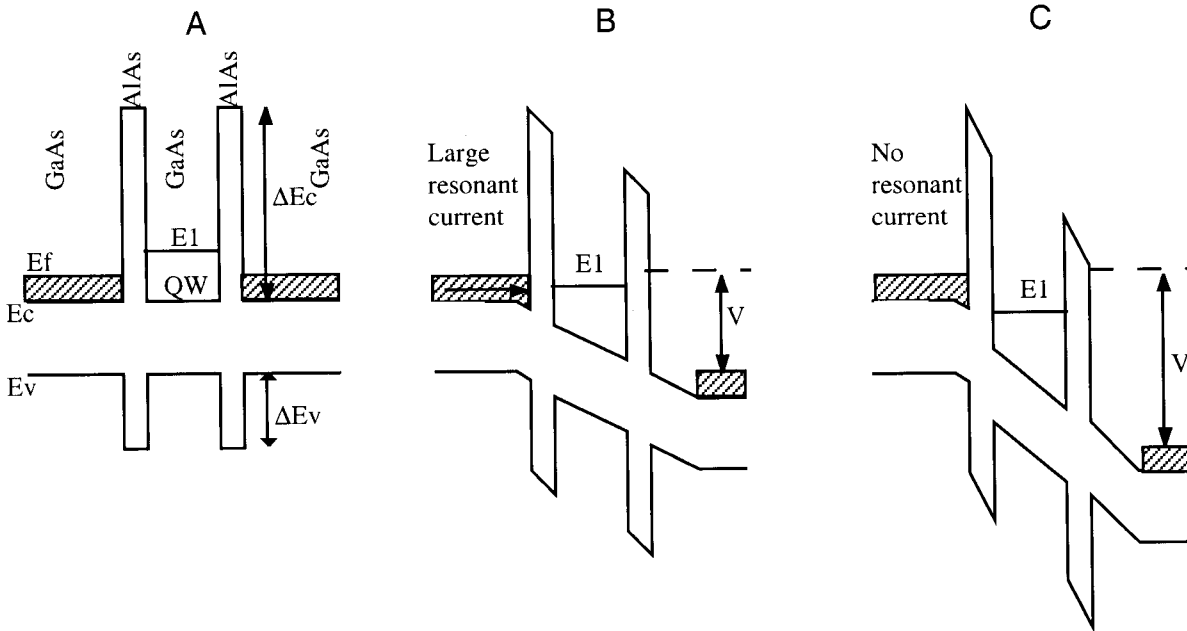
v) By the use of an interdigitated transistor structure such that the emitter contacts are only occupying the width of the emitter current crowding. [2]

vi) Because the input noise current for a FET is determined by the gate leakage current which is normally very small. [2]

vii) When using a grading in Ge (from high at the emitter side to low at the collector side) in the base  $\tau_b$  can be improved because the gradient causes an internal electric field in the base which enhances the diffusion by a drift term [2]

viii) No, because the gunn effect is caused by the special character of the band diagram of GaAs. Scattering of electrons from the  $\Gamma$  into the L band causes a negative differential velocity curve of GaAs on which the gunn effect is based. This feature is absent in Si. [2]

ix) [3]



x) Integration of digital (FET) and analogue rf electronics (Bipolar) for optimum speed (bipolar) and power consumption (FET) for hybrid designs, generally used in mobile communication systems. [1]