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

IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE
UNIVERSITY OF LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2000

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

ADVANCED ELECTRONIC DEVICES

Friday, 19 May 2000, 10:00 am

There are FIVE questions on this paper.

Answer THREE questions.

All questions carry equal marks.

Corrected Copy

Time allowed: 3:00 hours

Examiners: Dr K. Fobelets, Dr C. Juhasz

Special instructions for invigilators: None

Information for candidates:

$$V_0 = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2}$$

$$W_n = \sqrt{\frac{2\varepsilon_0\varepsilon_r}{q}(V_0 - V)\frac{N_A}{N_A N_D + N_D^2}}$$

$$W_p = \sqrt{\frac{2\varepsilon_0\varepsilon_r}{q}(V_0 - V)\frac{N_D}{N_A N_D + N_A^2}}$$

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

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

$$\sigma = q[\text{carrier concentration}]\mu$$

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

$$C_{diffusion} = \frac{2qI}{3kT}\frac{W^2}{2D}$$

q	=	$1.602\ 10^{-19}\ C$
n_i	=	$1.45\ 10^{10}\ cm^{-3}$ for Si at $300K$
n_i	=	$1.79\ 10^{6}\ cm^{-3}$ for GaAs at $300K$
kT/q	=	$0.026\ V$ at $300\ K$
ε_0	=	$8.854\ 10^{-12}\ F/m$
N_{CSi}	=	$2.8\ 10^{19}\ cm^{-3}$
N_{VSi}	=	$1.04\ 10^{19}\ cm^{-3}$
N_{CGaAs}	=	$4.7\ 10^{17}\ cm^{-3}$
N_{VGaAs}	=	$7\ 10^{18}\ cm^{-3}$
$\varepsilon_r^{SiO_2}$	=	4
ε_r^{Si}	=	11.7
ε_r^{GaAs}	=	13.1
E_G	=	$1.42\ eV$ for GaAs at $300K$
E_G	=	$2.18\ eV$ for AlAs at $300K$
E_G	=	$1.12\ eV$ for Si at $300K$
E_G	=	$0.66\ eV$ for Ge at $300K$

1

a) Give three sources of noise in semiconductor devices and explain their origin. [6]

b) The semi-empirical expression for the optimised noise figure in FETs is given by the Fukui equation: [4]

$$NF = 1 + K_F f C_{gs}\left[\left(R_g + R_s\right)/g_m\right]^{1/2}$$

Why is this expression independent of source resistance of the input circuit? Note that R_s in the formula is the source resistance of the FET.

c) The equivalent input noise sources for bipolar transistors (BT) and field effect transistors (FET) are given by:

$$BT \ : \ \langle v_i^2 \rangle = 4kT\left(r_b + 1/(2g_m)\right)\Delta f$$

$$\langle i_i^2 \rangle = 2q\frac{I_C}{\beta}\Delta f$$

$$FET \ : \ \langle v_i^2 \rangle = 4kT\frac{2}{3g_m}\Delta f$$

$$\langle i_i^2 \rangle = 2qI_G\Delta f$$

Calculate the optimum values of the input circuit source for both the BT and FET resistance when:

BT: $\beta = 200$
$g_m = 80mS$
$r_b = 4\ \Omega$ [10]
$I_C = q\ g_m/(kT)$

FET: $g_m = 5\ mS$
$V_{GS} = -2V$

Can the noise performance of FETs be worse than BTs and why (take the frequency range into account)?

2

a) Describe briefly the difference in gating action between a JFET and a MESFET. [4]

b) Draw the material cross section and the energy band diagram (E_c,E_v,E_f,E_g) from gate to substrate for both GaAs n-channel depletion mode JFET and MESFET. [6]

c) Consider a GaAs n-channel depletion mode JFET and MESFET with the same geometrical dimensions and channel doping density. Calculate the minimum channel thickness, at T=300K, for which the threshold voltage of both devices is the same.

JFET parameters: gate: $N_A = 10^{19}\ cm^{-3}$
channel: $N_D = 10^{17}\ cm^{-3}$

MESFET parameters: channel: $N_D = 10^{17}\ cm^{-3}$

Schottky barrier height: $q\phi_b = 0.4V$ [10]

3

Consider the band diagram of Figure 1 for two isolated semiconductors and consider the pn junction formed by bringing them together.

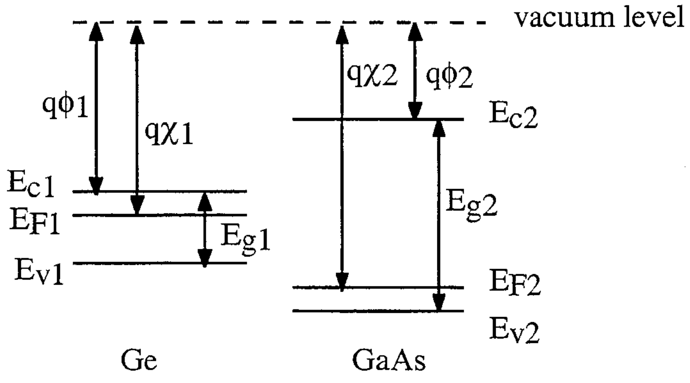


Figure 1: Band diagram for two isolated semiconductors: Ge and GaAs

a) Draw the energy band diagram for the pn hetero junction in equilibrium. [6]

b) Which current component (hole or electron) will dominate in forward bias and why? How can you achieve this in a homo junction pn diode? [4]

c) The gain of a planar npn homojunction bipolar transistor is given by:

$$\beta = \frac{D_n N_D L_e}{D_p N_A W_b}$$

How can the gain β be increased without decreasing the maximum oscillation frequency f_{max} defined by:

$$f_{max} = \frac{1}{4\pi}\sqrt{\frac{\omega_T}{r_{bb'}C_{b'c}}}?$$

The cut-off frequency f_T is given by: $f_T = \frac{qI_c}{2\pi kTC_{b'e}}$ [10]

Calculate the new increased value of the gain and the maximum oscillation frequency at room temperature for the transistor with the following parameters (see Fig.2):

Area: $A = 10^{-3} cm^2$	μ_n (emitter) = $1200\ cm^2/Vs$
N_D (emitter) = $10^{19}\ cm^{-3}$	μ_p (base) = $300\ cm^2/Vs$
N_A (base) = $10^{16}\ cm^{-3}$	μ_n (collector) = $2000\ cm^2/Vs$
N_D (collector) = $10^{18}\ cm^{-3}$	$I_c = 5\ mA$
$W_b = 10\ \mu m$	$V_{CE} = -5V$
$L_e = 4\ \mu m$	
$L_{eb} = 4\ \mu m$ distance between E and B contact	

Explain any approximation(s) you make during your calculations.

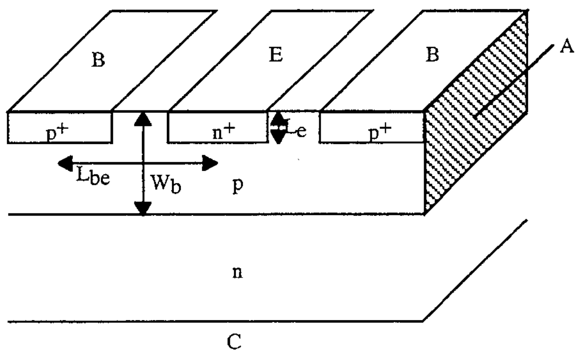


Figure 2: Schematic cross section of the planar BT

4

a) The velocity-field curve of GaAs is given in Figure 3. Explain why velocity overshoot occurs in this material. [4]

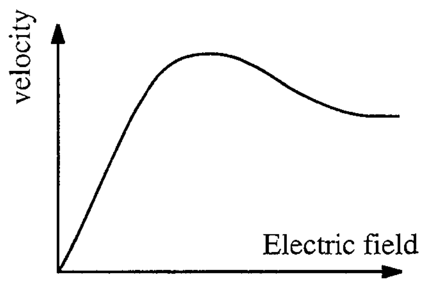


Figure 3: Velocity-field curve for GaAs

b) Give the equivalent circuit of a resonant tunnelling diode (RTD), explain the physical origin of the components and give the expression for the total impedance. [6]

c) Resonant tunnelling diodes can be used as oscillators. Give the conditions for which controlled oscillations can occur. Then calculate the maximum frequency for controlled oscillation for a GaAs/AlAs resonant tunnelling diode. The diode characteristics are: barrier width 2 nm, depletion width 200 nm, inductance of the contact wires 0.1 nL, negative differential resistance value 200 Ω. [10]

5)

a) Draw a parabolic energy band as a function of k (E-k). Add the graphs for the group velocity and the effective mass as a function of k. How are they related to the E-k graph? [4]

b) Sketch the density of states for a 3D, 2D and 1D system. [2]

c) Why is it impractical to bias the gate of a n^+p JFET to obtain maximum transconductance? [2]

d) Why can you expect diodes made using schottky contacts on semiconductor to be faster than pn-diodes? [2]

e) Draw a cross section of a AlGaAs/GaAs n-channel HEMT (high electron mobility transistor) and explain why the mobility of this HEMT is higher than that of an n-channel GaAs MESFET. [4]

f) Which carrier transport process determines the base transit time τ_{bt} in Si homojunction bipolar transistors (BJT) and how can τ_{bt} be decreased in SiGe:Si heterojunction bipolar transistors? [2]

g) Explain briefly (about 5 lines) the basic principles of a gunn diode and under which condition oscillation or amplification can occur. [4]

Answers

1

a)

i) Thermal noise or Johnson noise due to random thermal motion of charge carriers. Does not give a direct current but the average of the square of the velocity in non-zero. Occurs in resistive material.

ii) Shot noise is associated with a direct current flow. It originates from the discrete character of the charge and the random process in time in which charges are injected.

iii) 1/f noise or flicker noise is associated with a direct current and is assumed to be dependent on trap density.

b) In calculating the optimised noise figure the input circuit source resistance is replaced by its optimal value.

c) The expression of the optimal value of the source resistance is the same for BTs and FETs, and is given by:

$R_{sopt}^2 = \langle v_I^2\rangle / \langle i_I^2\rangle$

As calculated from: $NF = 1 + \langle v_I^2\rangle/(4kTR_s\Delta f) + \langle i_I^2\rangle/(4kT(1/R_s)\Delta f)$

BT: $R_{sopt}^2 = \langle v_I^2\rangle / \langle i_I^2\rangle$

$4kT(r_b + 1/(2\, g_m))/(2\, q\, I_c/\beta)$

$kT\, \beta\, (2\, g_m\, r_b + 1)/(g_m\, q\, I_c)$

$\beta\, (2\, g_m\, r_b + 1)/(g_m^2)$

$R_{sopt} = \sqrt{[\beta\, (2\, g_m\, r_b + 1)]}/\, g_m$

$R_{sopt} = 226\Omega$

FET: since the gate current is extremely small, one can put the input noise current to zero $\langle i_I^2\rangle = 0$.

$R_{sopt}^2 = \langle v_I^2\rangle / \langle i_I^2\rangle = \infty$, $R_{sopt} = \infty$

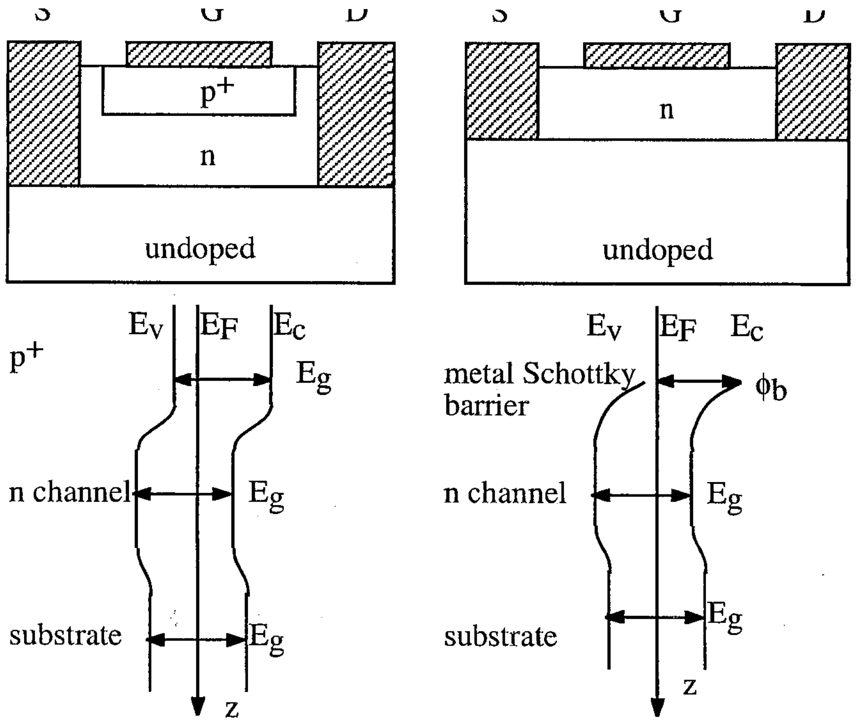
The noise performance of a device is dependent on the input circuit source resistance. FET will have excellent noise performance for large source resistance while for low source resistance NF. increases and can be larger than for the BT which gives the best noise performance at low source resistance. This in the frequency region lower than where $1/f^2$ noise becomes important in BTs.

2

a) JFET gating via pn junction where the region of the gate contact is more heavily doped than the channel region, ensuring depletion extends in the channel

MESFET gating is via a Schottky contact, which is a rectifying contact. Schottky metal directly only channel region.

b)



c) The threshold voltage is the gate voltage for which the channel layer is completely depleted. Depletion widths in the n-channel JFET is given by:

$$W_n = \left(\frac{2\varepsilon_0\varepsilon_r N_A\left(V_{bi}-V_G\right)}{qN_D\left(N_A+N_D\right)}\right)^{1/2} \approx \left(\frac{2\varepsilon_0\varepsilon_r\left(V_{bi}-V_G\right)}{qN_D}\right)^{1/2} \quad \textit{since } N_A >> N_D$$

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

The threshold voltage when W_n=a with a channel depth:

$$W_n = a = \left(\frac{2\varepsilon_0\varepsilon_r\left(V_{bi}-V_{T_{JFET}}\right)}{qN_D}\right)^{1/2}$$

$$V_{T_{JFET}} = V_{bi} - \frac{qN_D a^2}{2\varepsilon_0\varepsilon_r}$$

Depletion widths in the n-channel MESFET is given by:

$$W_n = \left(\frac{2\varepsilon_0\varepsilon_r\left(V_{bi}-V_G\right)}{qN_D}\right)^{1/2} \quad \text{since single sided junction}$$

with $V_{bi} = q\Phi_b - V_n$ where V_n is related to the difference : $E_c - E_f$

$V_n = ?$

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

$$\Rightarrow \quad E_c - E_f = kT\ln\left(\frac{N_C}{N_D}\right)$$

$$\Rightarrow \quad V_n = \frac{1}{q}\left(E_c-E_f\right) = \frac{kT}{q}\ln\left(\frac{N_C}{N_D}\right)$$

The threshold voltage when W_n=b with b channel depth:

$$W_n = b = \left(\frac{2\varepsilon_0\varepsilon_r \left(q\Phi_b - \frac{kT}{q}\ln\left(\frac{N_C}{N_D}\right) - V_{T_{MESFET}} \right)}{qN_D} \right)^{1/2}$$

$$V_{T_{MESFET}} = \frac{kT}{q}\ln\left(\frac{N_C}{N_D}\right) - q\Phi_b - \frac{qN_D b^2}{2\varepsilon_0\varepsilon_r}$$

$$V_{T_{JFET}} = V_{T_{MESFET}}$$

$$\frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) - \frac{qN_D a^2}{2\varepsilon_0\varepsilon_r} = \frac{kT}{q}\ln\left(\frac{N_C}{N_D}\right) - q\Phi_b - \frac{qN_D b^2}{2\varepsilon_0\varepsilon_r}$$

$$0.026\ln\left(\frac{10^{19}\,10^{17}}{(1.8\,10^6)^2}\right) - \frac{1.6\,10^{-19}\,10^{17}a^2}{2\,8.8\,10^{-14}13.1} = 0.026\ln\left(\frac{4.7\,10^{17}}{10^{17}}\right) - 0.4 - \frac{1.6\,10^{-19}\,10^{17}b^2}{2\,8.8\,10^{-14}13.1}$$

$$1.4 - 6.94\,10^9 a^2 = 0.04 - 0.4 - 6.94\,10^9\,b^2$$

$$6.94\,10^9 a^2 = 1.76 + 6.94\,10^9\,b^2$$

$$a^2 = b^2 + 2.54\,10^{-10} \quad [cm^2]$$

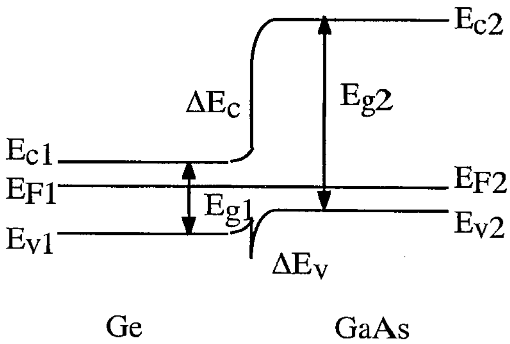
The depletion width at V_{GS}=0 for the MESFET is $W_n^M = 7.1\,10^{-6}$ cm

The depletion width at V_{GS}=0 for the JFET is $W_n^J = 1.4\,10^{-5}$ cm

The channel should be thicker than these values to have depletion operation. The minimum value for b=7.1 10^{-5} cm so a=1.7 10^{-5} cm.

3

a)



$\Delta E_C = q(\chi 1 - \chi 2)$

$\Delta E_V = \Delta E_g - \Delta E_C$

b) The hole current component will dominate in forward bias because the electrons travelling from Ge to GaAs see a large potential barrier at the interface (ΔE_c). To make the hole current larger than the electron current in homojunction pn diodes the p type region has to be more heavily doped than the n-type region.

c) The maximum oscillation frequency of the device is determined by $r_{bb'}$, $C_{b'c}$ and $C_{b'e}$, increasing the gain by decreasing the base doping or increasing the emitter doping would resp. increase $r_{bb'}$ and $C_{b'e}$. The use of an HBT though can increase the gain by a factor of $\exp\left(\frac{\Delta E_v}{kT}\right)$ with ΔE_v the valence band offset between emitter and base. Therefore we use $Al_{0.3}Ga_{0.7}As$ in the emitter and GaAs for collector and base.

$$\beta = \frac{D_n N_D L_e}{D_p N_A W_b}\exp\left[\frac{\Delta E_v}{kT}\right] = \frac{\mu_n N_D L_e}{\mu_p N_A W_b}\exp\left[\frac{\Delta E_v}{kT}\right]$$

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

$$\Delta E_v = \frac{2}{5}\left(30\%E_G^{AlAs} + 70\%E_G^{GaAs} - E_G^{GaAs}\right)$$

$$\Delta E_v = \frac{6}{50}\left(E_G^{AlAs} - E_G^{GaAs}\right)$$

$$\Delta E_v = \frac{6}{50}(2.18 - 1.42) = 0.09eV$$

$$\beta = \frac{1200\,10^{19}\;4\,10^{-4}}{300\,10^{16}\;10^{-3}}\exp\left[\frac{0.09(eV)}{0.026(eV)}\right] = 50985.5$$

Calculation of the maximum oscillation frequency:
Emitter-base is forward biased therefore the diffusion capacitance is larger than the depletion capacitance and thus $C_{b'e} = C_{diff}$

$$C_{b'e} = \frac{qI_c}{3kT}\frac{W_b^2}{D_h} = \frac{qI_c}{3kT}\frac{qW_b^2}{kT\mu_h}$$

The collector base capacitance is the depletion capacitance of the reversed biased junction. Since the doping density in the base is much lower than in the collector we can approximate the total

$$V_o = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2} = 0.026\ln\frac{10^{16}\;10^{19}}{\left(1.79\,10^{6}\right)^2} = 1.35V$$

$$W \approx W_p \approx \sqrt{\frac{2\varepsilon_0\varepsilon_r}{q}(V_0 - V)\frac{1}{N_D}}$$

depletion with by the depletion in the base only.
Only a small voltage drop will occur across the base-emitter junction since it is forward biased, we

$$C_{b'c} \approx \frac{\varepsilon_0\varepsilon_r A}{W_p} \approx \frac{\varepsilon_0\varepsilon_r A}{\sqrt{\frac{2\varepsilon_0\varepsilon_r}{q}(V_0 - V)\frac{1}{N_D}}} = \frac{8.85\,10^{-14}\;13.1\,10^{-3}}{\sqrt{\frac{2\;8.85\,10^{-14}\;13.1}{1.6\,10^{-19}\;10^{16}}(1.35+5)}} = 1.2\,10^{-11}\;F$$

therefore approximate the reverse bias voltage across the base-collector as –5V.

Base spreading resistance

$$r_{bb'} = \frac{\rho\,L_{eb}/2}{A} = \frac{L_{eb}/2}{\sigma\,A} = \frac{L_{eb}}{2q\mu_p pA} = \frac{4\,10^{-4}}{2\;1.6\,10^{-19}\;300\,10^{16}\;10^{-3}} = 0.42\Omega$$

$$f_{max} = \frac{1}{4\pi}\sqrt{\frac{\omega_T}{r_{bb'}C_{b'c}}} = \frac{1}{4\pi}\sqrt{\frac{qI_c}{kTr_{bb'}C_{b'e}C_{b'c}}} = \frac{1}{4\pi}\sqrt{\frac{3kTkT\mu_h qI_c}{kTr_{bb'}qI_c qW_b^2 C_{b'c}}}$$

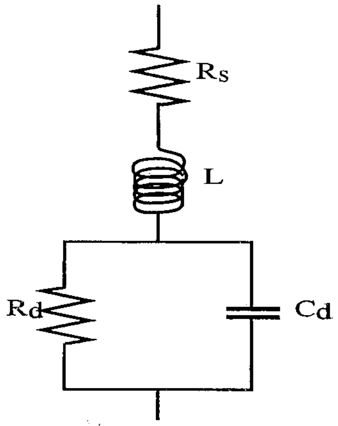
$$f_{max} = \frac{1}{4\pi}\sqrt{\frac{3kT\mu_h}{r_{bb'}qW_b^2C_{b'c}}} = \frac{1}{4\pi}\sqrt{\frac{3\;0.026\;300}{0.42\,10^{-6}\;1.2\,10^{-11}}} = 1.7\,10^{8}\;Hz$$

4)

a) Velocity overshoot occurs in GaAs because GaAs is a material where the X minimum in the conduction band at k≠0 lies very close

in energy to the Γ minimum at k=0. The electrons in the Γ minimum have lower effective mass values than in the upper valley. At low energies the majority of the electrons travel in the Γ minimum, at a certain electric field a large portion of the electrons have enough energy to transfer into the upper valley resulting in an increased average effective mass and thus a decreased velocity.

b)



R_s: series resistance due to contact resistance + semiconductor material resistance
C_d: capacitance due to undoped barriers surrounded by charge in series with the depletion layer capacitance
R_d: negative differential conductance, describing the N-shape of the IV curve.
L: inductance of the wires.
Total impedance:

$$Z_t = R_s + \frac{R_d}{1+\omega^2 C_d^2 R_d^2} + j\omega\left[L - \frac{C_d R_d^2}{1+\omega^2 C_d^2 R_d^2}\right]$$

c) Condition for oscillation and controlled oscillation are resp.: $R_s \le |R_d|$ and $f_{sr} > f_{rco}$
f_{sr} is the self resonance frequency occurring when $\mathrm{Im}(Z_t)=0$
f_{rco} is the resistive cut-off frequency occurring when $\mathrm{Re}(Z_t)=0$
Derive frequencies from total impedance:
f_{rco} :

$$\mathrm{Re}(Z_t) = R_s + \frac{R_d}{1+\omega_{rco}^2 C_d^2 R_d^2} = 0$$

$$\omega_{rco}^2 = \frac{-R_s - R_d}{C_d^2 R_d^2 R_s}$$

$$f_{rco} = \frac{1}{2\pi |R_d| C_d}\sqrt{\frac{|R_d|}{R_s} - 1}$$

f_{sr} :

$$\mathrm{Im}(Z_t) = L - \frac{C_d R_d^2}{1+\omega_{sr}^2 C_d^2 R_d^2} = 0$$

$$C_d^2 R_d^2 \omega_{sr}^2 = \frac{R_d^2 C_d}{L} - 1$$

$$f_{sr} = \frac{1}{2\pi |R_d| C_d}\sqrt{\frac{R_d^2 C_d}{L} - 1}$$

For controlled oscillations:

$$\frac{1}{2\pi |R_d| C_d}\sqrt{\frac{R_d^2 C_d}{L} - 1} > \frac{1}{2\pi |R_d| C_d}\sqrt{\frac{|R_d|}{R_s} - 1}$$

$$\frac{R_d^2 C_d}{L} - 1 > \frac{|R_d|}{R_s} - 1$$

$$R_s > \frac{L}{C_d |R_d|}$$

For controlled oscillations the series resistance needs to be $R_s \geq 34.5\Omega$.
Capacitance value C_d can be approximated to the depletion capacitance only since $L_b << W_{depl}$ and series connection of big (barrier) and small (depletion) capacitance.

$$C_d = A\left(\frac{\varepsilon_{GaAs}\varepsilon_o}{W_{depl}}\right)$$

$$C_d = 25\ 10^{-12}\left(\frac{13.1\ 8.85\ 10^{-12}}{200\ 10^{-9}}\right)$$

$$C_d = 14.5\ 10^{-15}F$$

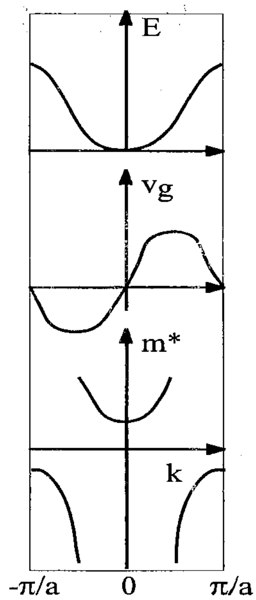
The smallest series resistance will give the largest oscillation frequency, therefore a minimum resistance value for controlled oscillation of R_s=34.5 Ω which gives:

$$f_{\max} = \frac{1}{2\pi|R_d|C_d}\sqrt{\frac{|R_d|}{R_s} - 1}$$

$$f_{\max} = 120GHz.$$

5

a)

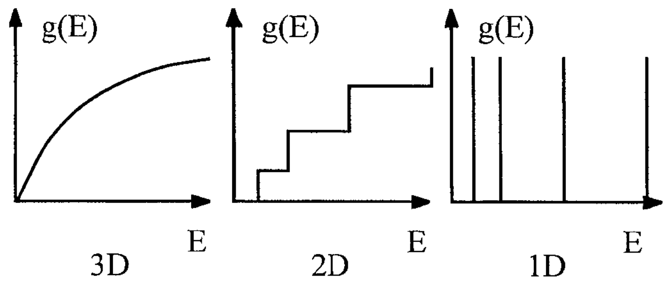


Energy band diagram dEαk²

Group velocity v_g α dE/dk

Effective mass m* α d²E/dk²

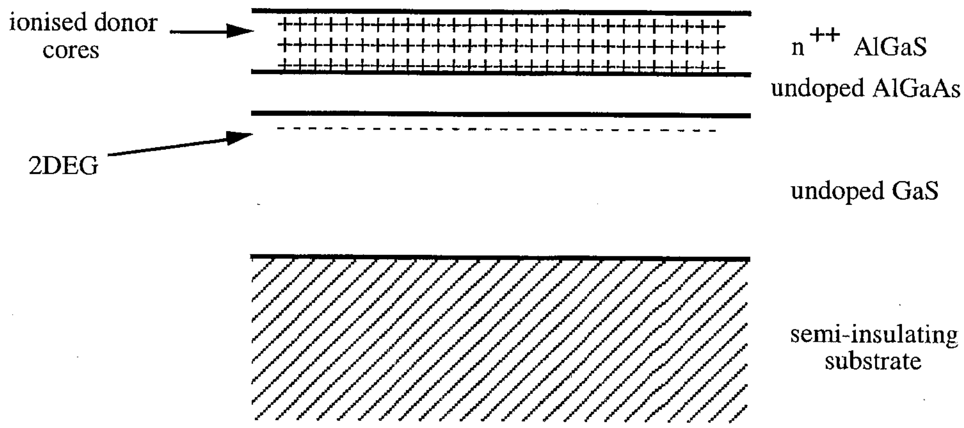
b)



c) It is impractical to bias the gate of a JFET at g_{mmax} since then the gate will be forward bias causing large leakage currents.

d) Schottky diodes function with majority carriers, so almost no minority carrier space charge has to be removed.

e)



Modulation doping has been used in HEMTs to ensure that the channel has no doping atoms. Carriers from the n+ doped AlGaAs fall in the quantum well formed by the AlGaAs/GaAs interface. This QW which forms the channel is undoped and therefore the impurity scattering is much reduced, increasing the speed of the carriers in the channel.

f) τ_{bt} in homojunction BJT is determined by diffusion of minority carriers through the base τ_{bt} is decreased in HBT when a gradient in Ge concentration is used in the base region. This will induce an electric field in the direction from C to E and adding drift to the electrons transport through the base.

g) A gunn diode is made of a material with a negative velocity-field characteristics. This characteristic will allow space charge domains to be formed. A space charge domain is a narrow dipole region which travels through the device. If the time taken to form a domain is smaller than the transit time through the device then the device can be used as an oscillator while otherwise it can be used as an amplifier.