Universiti Tun Hussein Onn Malaysia

UNIVERSITI TUN HUSSEIN ONN MALAYSIA

FINAL EXAMINATION
SEMESTER II
SESSION 2014/2015

COURSE NAME	:	ADVANCED SEMICONDUCTOR DEVICES
COURSE CODE	:	BED 41003
PROGRAMME	:	BACHELOR DEGREE OF ELECTRONIC ENGINEERING WITH HONOURS
EXAMINATION DATE	:	JUNE 2015 / JULY 2015
DURATION	:	3 HOURS
INSTRUCTION	:	1. ANSWER **ALL** QUESTIONS 2. ALL FINAL ANSWER MUST BE EXPRESSED IN **THREE SIGNIFICANT FIGURES.** 3. THE QUESTION PAPER MUST BE SUBMITTED WITH THE ANSWER BOOKLET.

THIS QUESTION PAPER CONSISTS OF **THIRTEEN (13)** PAGES

Q1 (a) Determine the strength of specific contact resistance, R_C, of X-Y junction at room temperature. Given that X is a metal, Y is a semiconductor, the effective Richardson constant is 114 $Acm^{-2}K^{-2}$, $\phi_m = 6.1$ V, $\phi_s = 6.7$ V, $\chi = \phi_m$.

(4 marks)

(b) A rectifying contact is normally formed at a metal-semiconductor junction when metal work function, ϕ_m, is greater than semiconductor work function, ϕ_s. Analyse how a non-rectifying contact can be formed using the same condition ($\phi_m > \phi_s$). Use an appropriate diagram to support your analysis.

(8 marks)

(c) (i) Suppose a heterojunction is formed between n-type Si and p-type GaAs. Formulate N_{GaAs} in term of N_{Si} if the maximum size of depletion region in n-type Si , W_{Si}, is 70 μm. Assume thermal equilibrium condition and the built-in potential is 1 V.

(7 marks)

(ii) Based on formulation in **Q1(c)(i)**, predict the minimum value of N_{Si} that will yield $N_{GaAs} > N_{Si}$.

(3 marks)

(d) Based on prediction in **Q1(c)(ii)**, deduce that the n-type Si must be highly doped to ensure the maximum of W_{Si} can be maintained.

(3 marks)

Q2 (a) A Si *p-i-n* diode as shown in Figure **Q2(a)** operates as a rectifier at low frequency. Calculate the rectifying current density, J_{re}, when applied forward bias, V_F, is 2.5 V. Given the effective carrier lifetime is 90 μs and the intrinsic region size is quadruple of doped-region at both ends.

(4 marks)

(b) Analyse how a Si *p-i-n* diode acts as a current-controlled RF resistor at high frequency. Show the related resistance-current characteristic in your analysis.

(8 marks)

(c) Figure **Q2(c)(i)** shows the device structure, doping profile, electric field distribution and ionisation integrand of a hi-lo IMPATT diode. Suppose the device structure is modified as shown in Figure **Q2(c)(ii)**. Predict the doping profile, electric field distribution and ionisation integrand of the modified device. Draw all required device characteristics in Figure **Q2(c)(ii)**.

(10 marks)

(d) Deduce a type of IMPATT diode that has similar characteristics predicted in **Q2(c)**.

(3 marks)

Q3 (a) Referring to Figure **Q3(a)**, determine the change of breakdown voltage in SCR due to avalanche mechanism, in percentage, when the *n*-layer width changes from 10 μm to 40 μm. All required values must be marked clearly in Figure **Q3(a)**.
(4 marks)

(b) Resonant tunnelling diode operates on the concept of tunnelling probability and creation of tunnelling current. Analyse how the tunnelling current is made possible in the perspective of device structure. Show appropriate diagram to support your analysis.
(8 marks)

(c) An SCR can be modelled as a series of pnp and npn transistors in forward blocking and forward breakover modes.

(i) Formulate the holding current, I_h, in term of gate current, I_g, at the point of breakover mode given the following data:

- $2.0 \times 10^{-3} \leq I_{CO1} \leq 4.5 \times 10^{-3}\ A$
- $1.5 \times 10^{-3} \leq I_{CO2} \leq 2.5 \times 10^{-3}\ A$
- $0.8\alpha_{2(min)} \leq \alpha_1 \leq 0.64$
- $0.4 \leq \alpha_2 \leq 0.25\alpha_{1(max)}$

(6 marks)

(ii) Using formulation in **Q3(c)(i)**, predict the required I_g if the SCR turns into conduction mode only if both I_h and I_g equals.
(4 marks)

(d) Deduce **ONE (1)** factor that enables DMOS to sustain high breakdown voltage.
(3 marks)

Q4 (a) Determine the resistance imposed by a Ge *n*-type MESFET of L = 100 μm and its width is five times of its length. Given the doping concentration is 10^{14} cm^{-3}.
(4 marks)

(b) Analyse **THREE (3)** conditions that contribute to ballistic motion in hot electron mechanism. Show appropriate diagram to support your analysis.
(8 marks)

(c) Consider the normal operation of an *n*-type Si JFET with V_{GS}=0 and V_D>V_S.

(i) Formulate the maximum pinch-off current in term of its doping concentration, N_D, given that the metallurgical thickness is kept to be not more than 15 μm. Assume the device width is quadruple of its length.
(6 marks)

(ii) Based on relationship formulated in **Q4(c)(i)**, predict the range of maximum pinch-off current if $10^{15} \leq N_D \leq 10^{17}$ cm^{-3}.
(4 marks)

(d) In saturation region operation, the pinch off area separates the *n*-channel between source and drain terminals. Deduce the reason the electron still able to flow through pinch off region in this operation.

(3 marks)

- END OF QUESTION -

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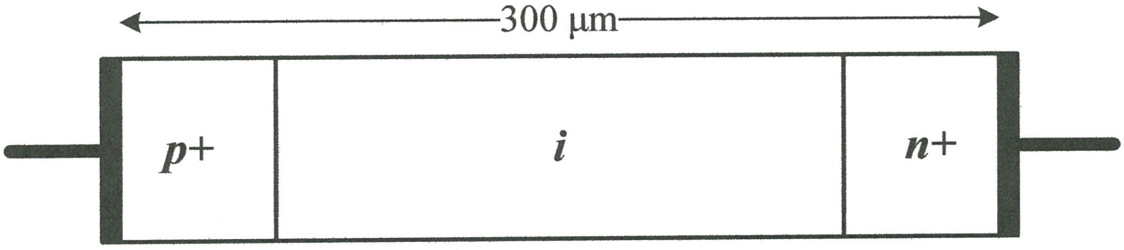

FIGURE Q2(a)

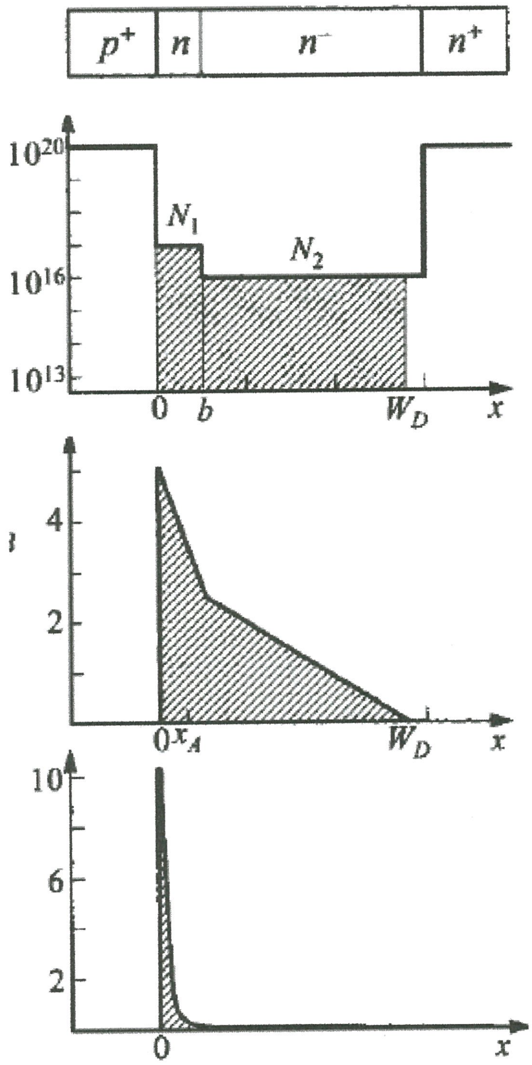

FIGURE Q2(c)(i)

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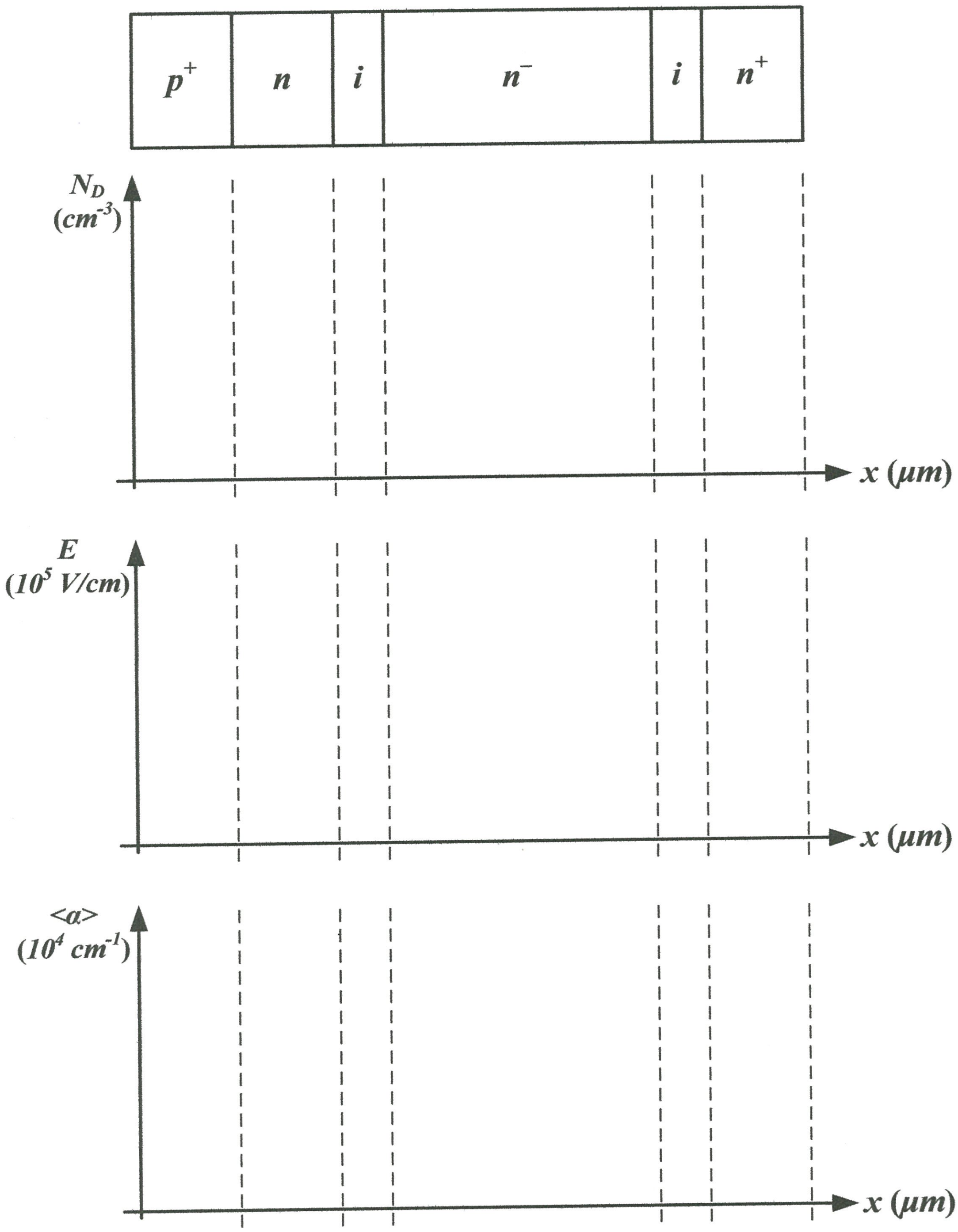

FIGURE Q2(c)(ii)

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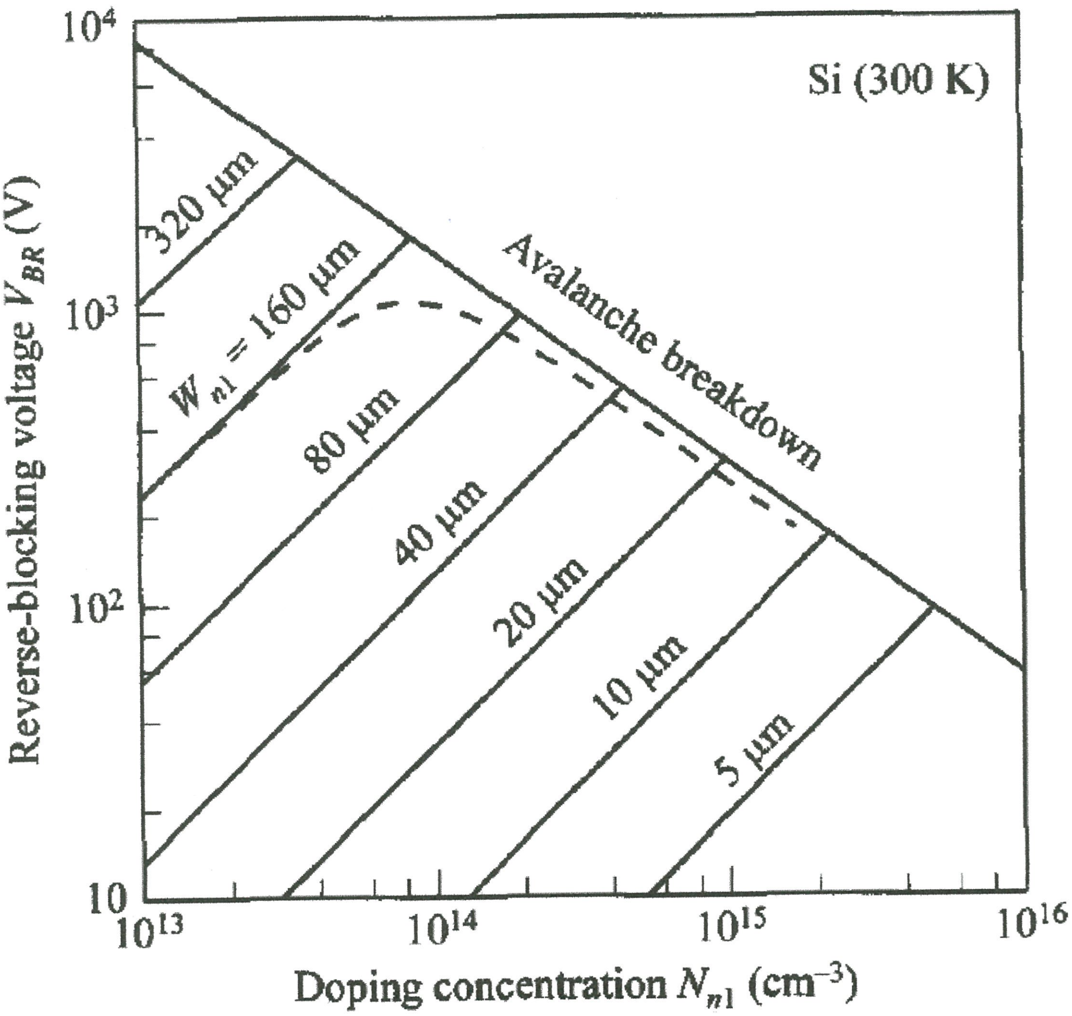

FIGURE Q3(a)

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Table 1 Physical constants

Avogadro's number	$N_A = 6.02 \times 10^{23}$ atoms per gram molecular weight
Boltzmann's constant	$k = 1.38 \times 10^{-23}$ J/K $= 8.62 \times 10^{-5}$ eV/K
Electronic charge (magnitude)	$q = 1.6 \times 10^{-19}$ C
Free electron rest mass	$m_0 = 9.11 \times 10^{-31}$ kg
Permeability of free space	$\mu_0 = 4\pi \times 10^{-7}$ H/m
Permittivity of free space	$\varepsilon_0 = 8.85 \times 10^{-14}$ F/cm $= 8.85 \times 10^{-12}$ F/m
Planck's constant	$h = 6.625 \times 10^{-34}$ J-s $= 4.135 \times 10^{-15}$ eV-s
Modified Planck's constant	$\hbar = 1.054 \times 10^{-34}$ J-s
Proton rest mass	$M = 1.67 \times 10^{-27}$ kg
Speed of light in vacuum	$c = 2.98 \times 10^{10}$ cm/s
Thermal voltage (T = 300 K)	$V_t = kT/q = 0.0259$ V

Table 2 Work function of selected metals

Metal	Work function (V)
Silver (Ag)	4.26
Aluminum (Al)	4.28
Gold (Au)	5.10
Titanium (Ti)	4.33
Tungsten (W)	4.55

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Table 3 Silicon, Gallium Arsenide and Germanium properties (T = 300 K)

Property	**Si**	**GaAs**	**Ge**
Atoms (cm^{-3})	5.0×10^{22}	4.42×10^{22}	4.42×10^{22}
Atomic weight	28.09	144.63	72.60
Density (g/cm^{-3})	2.33	5.32	5.33
Lattice constant (Å)	5.43	5.65	5.65
Melting point (°C)	1415	1238	937
Dielectric constant	11.7	13.1	16.0
Bandgap energy (eV)	1.12	1.42	0.66
Electron affinity, χ (volts)	4.01	4.07	4.13
Effective density of states in conduction band, N_c (cm^{-3})	$2.8\ 10^{19}$	4.7×10^{17}	1.04×10^{19}
Effective density of states in valence band. N_v (cm^{-3})	1.04×10^{19}	7.0×10^{18}	6.0×10^{18}
Intrinsic carrier concentration (cm^{-3})	1.5×10^{10}	1.8×10^{6}	2.4×10^{13}
Mobility (cm^2/V-s)			
Electron, μ_n	1350	8500	3900
Hole, μ_p	480	400	1900
Effective mass (density of states)			
Electrons $\left(\frac{m_n^*}{m_0}\right)$	1.08	0.067	0.55
Holes $\left(\frac{m_p^*}{m_0}\right)$	0.56	0.48	0.37

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Table 4 List of formula

Schottky barrier

1. $q\phi_{Bn0} = q(\phi_m - \chi)$
2. $q\phi_{Bp0} = E_g - q(\phi_m - \chi)$
3. $q\psi_{bi} = q(\phi_{Bn0} - \phi_n)$
4. $Q_{sc} = qN_D W_D = \sqrt{2q\varepsilon_s N_D \psi_{bi}}$
5. $|E_{\max}| = \dfrac{qN_D x_n}{\varepsilon_s}$
6. $x_n = \sqrt{\dfrac{2\varepsilon_s \psi_{bi}}{qN_D}}$
7. $J = \left[A^* T^2 \exp\left(-\dfrac{e\phi_{Bn0}}{kT}\right)\right]\left[\exp\left(\dfrac{eV_F}{kT}\right) - 1\right]$
8. $J = J_{sT}\left[\exp\left(\dfrac{eV_F}{kT}\right) - 1\right]$
9. $Q_{ss} = -qD_{it}(E_g - q\phi_0 - q\phi_{Bn0})$
10. $Q_M = -(Q_{ss} + Q_{sc})$
11. $Q_{sc} = \sqrt{2q\varepsilon_s N_D\left(\phi_{Bn0} - \phi_n - \dfrac{kT}{q}\right)}$
12. $\Delta = \phi_m - (\chi + \phi_{Bn0}) = -\dfrac{\delta Q_M}{\varepsilon_i}$

Ohmic contact

13. $\phi_{Bn} = \phi_n$
14. $J_t \propto \exp\left(-\dfrac{q\phi_{Bn}}{E_{00}}\right)$
15. $E_{00} = \dfrac{e\hbar}{2}\sqrt{\dfrac{N_d}{\varepsilon_s m_n^*}}$
16. $R_C = \dfrac{k}{A^{**}Tq}\exp\left(\dfrac{q\phi_{Bn}}{kT}\right)$
17. $R_C = \dfrac{\left(\dfrac{kT}{q}\right)\exp\left(\dfrac{q\phi_{Bn}}{kT}\right)}{A^* T^2}$
18. $R = \dfrac{R_C}{A}$

Heterojunction

19. $\psi_{bi} = |\phi_{m1} - \phi_{m2}|$
20. $W_{D1} = \sqrt{\dfrac{2N_2\varepsilon_{s1}\varepsilon_{s2}(\psi_{bi} - V)}{qN_1(\varepsilon_{s1}N_1 + \varepsilon_{s2}N_2)}}$
21. $W_{D2} = \sqrt{\dfrac{2N_1\varepsilon_{s1}\varepsilon_{s2}(\psi_{bi} - V)}{qN_2(\varepsilon_{s1}N_1 + \varepsilon_{s2}N_2)}}$
22. $C_D = \sqrt{\dfrac{qN_1N_2\varepsilon_{s1}\varepsilon_{s2}}{2(\varepsilon_{s1}N_1 + \varepsilon_{s2}N_2)(\psi_{bi} - V)}}$
22. $J_n = \dfrac{qD_{n2}n_{i2}^2}{L_{n2}N_2}\left[\exp\left(\dfrac{qV}{kT}\right) - 1\right]$
24. $J_p = \dfrac{qD_{p1}n_{i1}^2}{L_{p1}N_1}\left[\exp\left(\dfrac{qV}{kT}\right) - 1\right]$
25. $\dfrac{J_n}{J_p} \approx \dfrac{N_1}{N_2}\exp\left(-\dfrac{\Delta E_g}{kT}\right)$
26. $J = qN_{D2}\sqrt{\dfrac{kT}{2\pi m_2^*}}\exp\left(\dfrac{q\psi_{b2}}{kT}\right)\left[\exp\left(\dfrac{qV_2}{kT}\right) - \exp\left(\dfrac{-qV_1}{kT}\right)\right]$

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Table 4 List of formula (Cont..)

Varactor and *p-i-n* diodes

27. $N = Bx^m$

28. $\psi(x=0)=0; \quad \psi(x=W_D)=V_R+\psi_{bi}$

29. $W_D = \left[\dfrac{\varepsilon_s (m+2)(V_R+\psi_{bi})}{qB}\right]^{\frac{1}{m+2}}$

30. $C_D = \dfrac{\varepsilon_s}{W_D} = \left[\dfrac{qB\varepsilon_s^{m+1}}{(m+2)(V_R+\psi_{bi})}\right]^{\frac{1}{m+2}}$

31. $s = \dfrac{1}{m+2}$

32. $t_{sw} = \dfrac{W}{v_s}$

33. $C = \dfrac{\varepsilon_s}{W}$

34. $V_{BD} = \mathbf{E}_m W$

35. $J_{re} = \dfrac{qWn_i}{2\tau}\exp\left(\dfrac{qV_F}{2kT}\right)$

36. $R_{RF} = \rho\dfrac{W}{A} = \dfrac{W}{q\Delta n(\mu_n+\mu_p)\ A}$

IMPATT diodes

37. $\langle\alpha\rangle = \alpha_n \exp\left[-\int_x^{W_D} \alpha_n - \alpha_p dx'\right] \quad (\alpha_n > \alpha_p)$

38. $\int_x^{W_D} \langle\alpha_n\rangle dx = 1$

39. $V_B = \dfrac{1}{2}\mathrm{E}_m W_D = \dfrac{\varepsilon_s \mathrm{E}_m^2}{2qN} \cdots (1-sided)$

40. $V_B = \dfrac{1}{2}\mathrm{E}_m W_D = \dfrac{\varepsilon_s \mathrm{E}_m^2}{qN} \cdots (2-sided)$

41. $V_B = \mathrm{E}_m W_D - \dfrac{qN_1 b}{\varepsilon_s}\left(W_D - \dfrac{b}{2}\right) \cdots (read)$

42. $V_B = \dfrac{\mathrm{E}_m b}{2} + \dfrac{qN_2 W_D (W_D - b)}{2\varepsilon_s} \cdots (hi-lo)$

43. $V_B = \mathrm{E}_m b + \left(\mathrm{E}_m - \dfrac{qQ}{\varepsilon_s}\right)(W_D - b) \cdots (lhil)$

44. $\int_0^{x_A} \langle\alpha\rangle dx = 0.95$

45. $\mathrm{E}_{\min} = \mathrm{E}_m - \dfrac{q[N_1 b + N_2 (W_D - b)]}{\varepsilon_s}$

46. $I = Aq\Delta n v_s$

47. $\Delta\mathrm{E}(x) = \dfrac{Ix}{A\varepsilon_s v_s}$

48. $\Delta V_B = I\dfrac{(W_D - x_A)^2}{2A\varepsilon_s v_s}$

49. $R_{SC} = \dfrac{(W_D - x_A)^2}{2A\varepsilon_s v_s}$

50. $V_m = \mathrm{E}_m W_D$

51. $J_m = \dfrac{\mathrm{E}_m \varepsilon_s v_s}{W_D}$

52. $P_m = V_m J_m = \mathrm{E}_m^2 \varepsilon_s v_s$

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Table 4 List of formula (Cont..)

Thyristors

53. $V_B \approx 6.0\times 10^{13}(N_{n1})^{-0.75}$

54. $V_{PT} = \dfrac{qN_{n1}W_{n1}^2}{2\varepsilon_s}$

55. $V_{BR} = V_B(1-\alpha_1)^{\frac{1}{n}}$

56. $V_{BR} = \text{sech}\left(\dfrac{W_{n1}}{L_{n1}}\left(1-\sqrt{\dfrac{V_{AK}}{V_{PT}}}\right)\right)$

57. $I_A = \dfrac{\alpha_2 I_g + I_{CO1} + I_{CO2}}{1-(\alpha_1+\alpha_2)}$

58. $I = \dfrac{1}{\alpha_1+\alpha_2}[\alpha_1(I)I + \alpha_2(I)I + I_0]$

59. $V_{BF} = V_B(1-\alpha_1-\alpha_2)^{1/n}$

60. $V_{AK} = V_1 + V_2 + V_3$

61. $J = \dfrac{qnW_i}{\tau_{eff}}$

62. $\tau_{eff} = \dfrac{1}{\left(2A_r n^2 + \dfrac{1}{\tau_{p0}+\tau_{n0}}\right)}$

Resonant tunneling devices

63. $E_n - E_{Cw} = \dfrac{h^2n^2}{8m^*W^2}..$

64. $E_w = E_n + \dfrac{h^2k_\perp^2}{2m^*}$

65. $E = E_C + \dfrac{h^2k^2}{2m^*} = E_C + \dfrac{h^2k_x^2}{2m^*} + \dfrac{h^2k_\perp^2}{2m^*}$

66. $V_P \approx \dfrac{2(E_n - E_C)}{q}$

Hot electron devices

67. $f(v) = e^{E_F/kT_e} e^{-\left(\frac{mv^2}{2} - m\langle v\rangle\bullet v\right)/kT_e}$

68. $\langle E\rangle = \dfrac{3}{2}kT_e + \dfrac{1}{2}m\langle v\rangle^2,\quad T_e >> E_F$

69. $\langle E\rangle = \dfrac{3}{5}E_F + \dfrac{1}{2}m\langle v\rangle^2,\quad E_F >> kT_e$

70. $E_F = (3\pi^2)^{3/2}\dfrac{\hbar}{2m}n^{3/2}$

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Table 4 List of formula (Cont..)

JFET

71. $h = \sqrt{\dfrac{2\varepsilon_s(V_{bi} + V_{DS} - V_{GS})}{qN_D}}$

72. $I_D = I_P\left[3\left(\dfrac{V_{DS}}{V_{p0}}\right) - 2\left(\dfrac{V_{DS} + V_{bi} - V_{GS}}{V_{p0}}\right)^{3/2} + 2\left(\dfrac{V_{bi} - V_{GS}}{V_{p0}}\right)^{3/2}\right]$

73. $V_{p0} = \dfrac{qa^2N_d}{2\varepsilon_s}$

74. $I_P = \dfrac{\mu_n(qN_d)^2Wa^3}{6\varepsilon_sL}$

75. $V_{Dsat} = V_{p0} - (V_{bi} - V_{GS})$

76. $I_{Dsat} = I_P\left[1 - 3\left(\dfrac{V_{bi} - V_{GS}}{V_{p0}}\right)\left(1 - \dfrac{2}{3}\sqrt{\dfrac{V_{bi} - V_{GS}}{V_{p0}}}\right)\right]$

MESFET

77. $R = \dfrac{L}{q\mu_nN_DA}$

78. $I_D = \dfrac{V_D}{R}$

79. $I_D = I_P\left[\dfrac{V_D}{V_P} - \dfrac{2}{3}\left(\dfrac{V_D + V_G + V_{bi}}{V_P}\right)^{3/2} + \dfrac{2}{3}\left(\dfrac{V_G + V_{bi}}{V_P}\right)^{3/2}\right]$

80. $V_P = \dfrac{qN_Da^2}{2\varepsilon_s}$

81. $I_P = \dfrac{Z\mu_nq^2N_D^2a^3}{2\varepsilon_sL}$

82. $I_{Dsat} = I_P\left[\dfrac{1}{3} - \left(\dfrac{V_G + V_{bi}}{V_P}\right) + \dfrac{2}{3}\left(\dfrac{V_G + V_{bi}}{V_P}\right)^{3/2}\right]$

83. $V_{Dsat} = \dfrac{qN_Da^2}{2\varepsilon_s} - V_{bi} - V_G$

84. $V_B = V_D + |V_G|$

85. $g_m = \dfrac{I_PV_D}{2V_P^2}\sqrt{\dfrac{V_P}{V_G + V_{bi}}}$, *lin*

86. $g_m = \dfrac{I_P}{V_P}\left(1 - \sqrt{\dfrac{V_G + V_{bi}}{V_P}}\right)$, *sat*

MODFET

87. $V_P = \dfrac{qN_Dd_1^2}{2\varepsilon_s}$

88. $V_T = \phi_{Bn} - \dfrac{\Delta E_C}{q} - V_P$

89. $I = \dfrac{Z}{L}\mu_nC_i(V_G - V_T)V_D$

90. $V_{Dsat} = V_G - V_T$

91. $I_{sat} = \dfrac{Z\mu_n\varepsilon_s}{2L(d_1 + d_0 + \Delta d)}(V_G - V_T)^2$