UTHM
Universiti Tun Hussein Onn Malaysia

UNIVERSITI TUN HUSSEIN ONN MALAYSIA

FINAL EXAMINATION
SEMESTER II
SESSION 2015/2016

COURSE NAME	:	ADVANCED SEMICONDUCTOR DEVICES
COURSE CODE	:	BED 41003
PROGRAMME	:	BEJ
EXAMINATION DATE	:	JUNE / JULY 2016
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 **TWELVE** (**12**) PAGES

Q1 (a) Explain the concept of wave nature of carriers that results in fundamental operation of tunnelling diodes.

(2 marks)

(b) Suppose an anisotype heterojunction is formed between *n*-type Si with $N_D = 10^{14}$ cm^{-3} and *p*-type Ge with $N_A = 3 \times 10^{17}$ cm^{-3}. Determine the built-in potential and the depletion width of this heterojunction.

(8 marks)

(c) Analyse how built-in potential of Schottky barrier, ψ_{bi}, is affected when forward bias and reverse bias are applied on a metal-semiconductor junction. You may use the appropriate diagram to support your analysis.

(6 marks)

(d) Referring to **Figure Q1(d)**, analyse the reason that the electron tunnelling could occur at the *n-n* isotype heterojunction.

(6 marks)

(e) Predict the change in depletion region of a Schottky barrier, x_n, when the built-in potential, ψ_{bi}, is tripled.

(3 marks)

Q2 (a) Explain the purpose of having undoped spacer next to barrier in resonant tunnelling diode.

(2 marks)

(b) A GaAs hi-lo IMPATT diode has the following parameters:

$$N_2 = 10^{14} \text{ cm}^{-3},\ W_D = 20\ \mu\text{m},\ E_m = 3 \times 10^7 \text{ V/cm and } b = 4\ \mu\text{m}.$$

Calculate the doping concentration of *n*-layer, N_1, and the breakdown voltage, V_B.

(8 marks)

(c) Analyse the correlation of depletion width size, W_D, and sensitivity, s, with the capacitance of a varactor. Show the related formulas to support your analysis.

(8 marks)

(d) Analyse how the quantum well design in resonant tunnelling diode enable the carrier movement during device operation. You may use appropriate diagram to support your analysis.

(4 marks)

(e) Predict the change on current conduction in a *p-i-n* diode when the external bias is doubled, assuming other parameters are unchanged.

(3 marks)

Q3 (a) Explain **ONE (1)** advantage of hot electron in semiconductor device application.
(2 marks)

(b) Determine the current gain, α_1, natural region of n_1 layer, W, of a Ge SCR when it is in the reverse blocking mode. Given the intrinsic layer width, W_{n1}, is 80 μm and the length, L_{n1}, is 100 μm. Assume that the anode-to-cathode voltage, V_{AK}, is half of the punchthrough voltage, V_{PT} in this mode.
(8 marks)

(c) Referring to **Figure Q3(c)(i)**, analyse the factor that cause the reduction of V_{AK} when SCR turns from forward breakover mode into conduction mode. Draw the energy-band diagram in **Figure Q3(c)(ii)** as part of your analysis.
(8 marks)

(d) Analyse **TWO (2)** conditions that promote carriers movement into ballistic motion in semiconductor.
(4 marks)

(e) Referring to DMOS structure in **Figure Q3(e)**, predict the changes of depletion region when doping concentration of *n* layer is reduced.
(3 marks)

Q4 (a) Explain the main factor of quasi-thermal phenomenon in semiconductor device.
(2 marks)

(b) Determine the current and saturation current of a square *n*-type MODFET, given the thickness of undoped and doped regions are 5 μm and 1 μm respectively. The device operates with drain voltage, V_D = 200 mA, gate voltage, V_G is 50 mV higher than the threshold voltage, V_T, and the capacitance density, C_i = 50 μF/cm^2. Assume that the Δd is one-tenth of the doped region.
(8 marks)

(c) Analyse the importance of having $V_G \leq 0$ and $V_D \geq 0$ in normal operation of a depletion mode *n*-type MESFET.
(6 marks)

(d) Analyse the main contributing factor that causes depletion region in *n*-type JFET grows uneven as shown in **Figure Q4(d)**. In addition, analyse the reason I_{DS} continues to flow in this condition.
(6 marks)

(e) Predict the changes in depletion charge width, h, when the doping concentration of substrate, N_D, is increased by 100 times.
(3 marks)

- END OF QUESTIONS -

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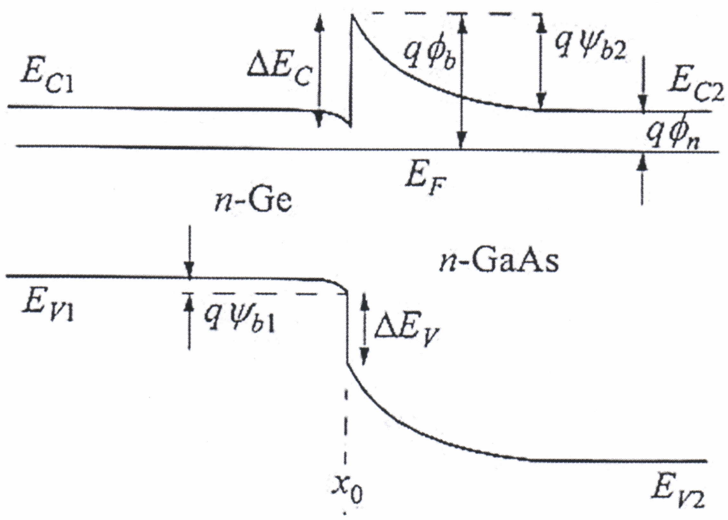

Figure Q1(d)

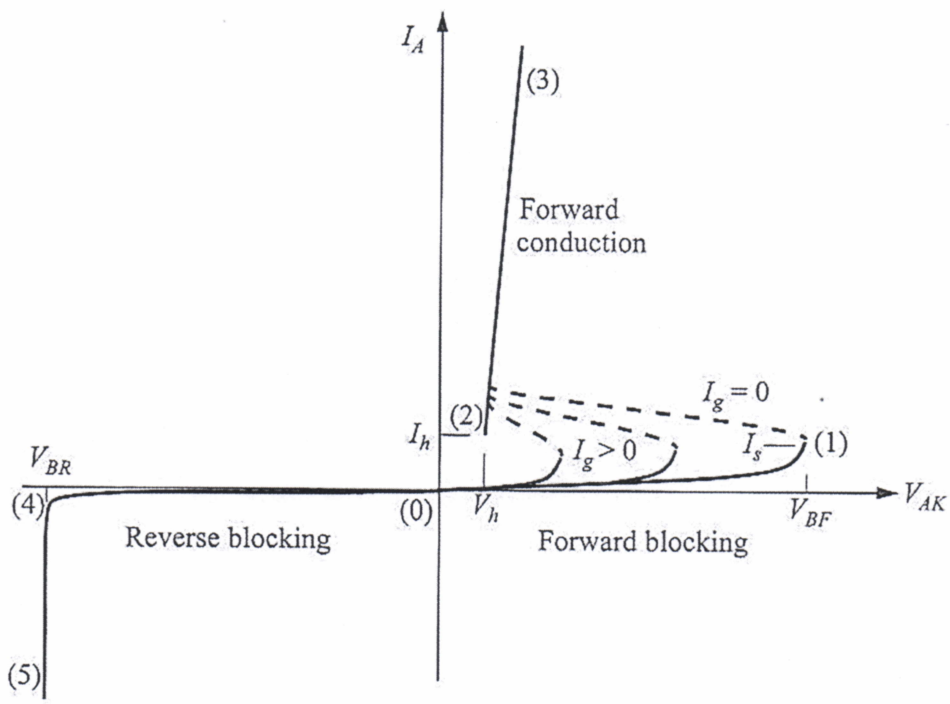

Figure Q3(c)(i)

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****Draw the band diagram in this sheet****

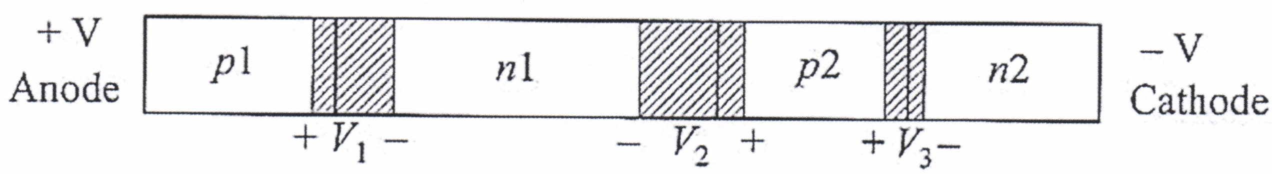

Figure Q3(c)(ii)

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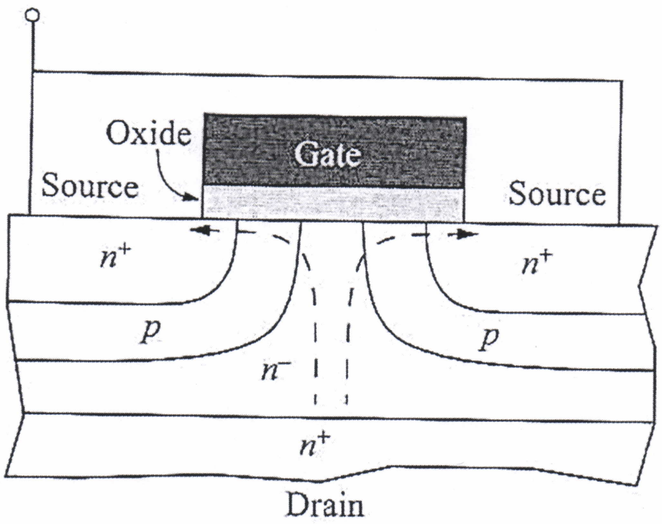

Figure Q3(e)

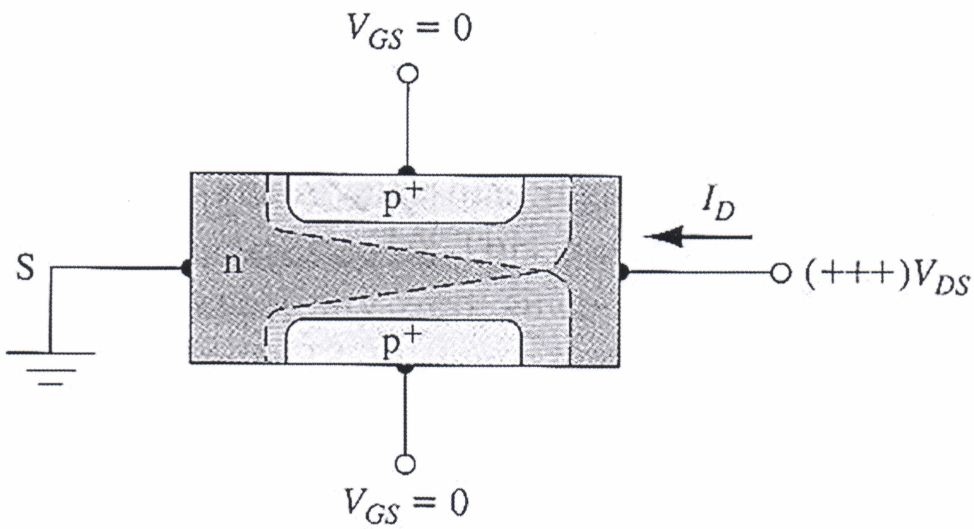

Figure Q4(d)

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Table 1 Physical constants

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 ($cm^2/V\text{-}s$)			
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. $Q_{ss} = -qD_{it}\left(E_g - q\phi_0 - q\phi_{Bn0}\right)$

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

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

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

56. $\alpha_1 = \text{sech}\left(\dfrac{W}{L_{n1}}\right)$

57. $W = W_{n1}\left(1-\sqrt{\dfrac{V_{AK}}{V_{PT}}}\right)$

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

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

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

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

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

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

Hot electron devices

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

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

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

74. $I_P = \dfrac{\mu_n (qN_d)^2 W a^3}{6\varepsilon_s L}$

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. $R = \dfrac{L}{q\mu_n N_D A}$

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

81. $I_P = \dfrac{Z\mu_n q^2 N_D^2 a^3}{2\varepsilon_s L}$

82. $I_{Dsat} = I_P \left[\dfrac{1}{3} - \left(\dfrac{V_G + V_{bi}}{V_{P0}}\right) + \dfrac{2}{3}\left(\dfrac{V_G + V_{bi}}{V_{P0}}\right)^{3/2} \right]$

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

84. $V_B = V_D + |V_G|$

85. $g_m = \dfrac{I_P V_D}{2V_{P0}^2}\sqrt{\dfrac{V_{P0}}{V_G + V_{bi}}}, \quad lin$

86. $g_m = \dfrac{I_P}{V_{P0}}\left(1 - \sqrt{\dfrac{V_G + V_{bi}}{V_{P0}}}\right), \quad sat$

MODFET

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

88. $V_T = \phi_{Bn} - \dfrac{\Delta E_C}{q} - V_{P0}$

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

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

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