electronic devices and circuit theory

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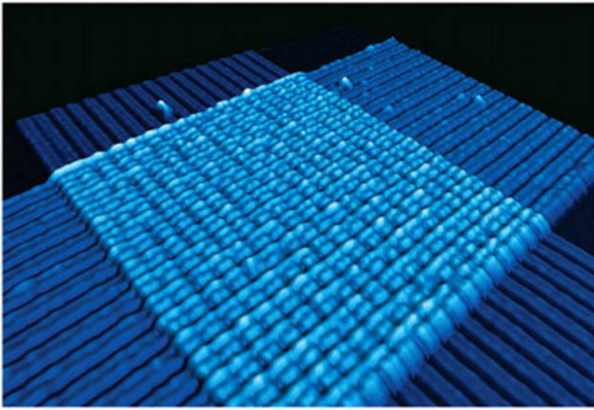

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SIGNIFICANT EQUATIONS

1 Semiconductor Diodes $W = QV$, $1\text{ eV} = 1.6 \times 10^{-19}\text{ J}$, $I_D = I_s(e^{V_D/nV_T} - 1)$, $V_T = kT/q$, $T_K = T_C + 273°$, $k = 1.38 \times 10^{-23}\text{ J/K}$, $V_K \cong 0.7\text{ V (Si)}$, $V_K \cong 0.3\text{ V(Ge)}$, $V_K \cong 1.2\text{ V (GaAs)}$, $R_D = V_D/I_D$, $r_d = 26\text{ mV}/I_D$, $r_{av} = \Delta V_d/\Delta I_d|_{\text{pt. to pt.}}$, $P_D = V_D I_D$, $T_C = (\Delta V_Z/V_Z)/(T_1 - T_0) \times 100\%/°\text{C}$

2 Diode Applications Silicon: $V_K \cong 0.7$ V, germanium: $V_K \cong 0.3$ V, GaAs: $V_K \cong 1.2$ V; half-wave: $V_{dc} = 0.318V_m$; full-wave: $V_{dc} = 0.636V_m$

3 Bipolar Junction Transistors $I_E = I_C + I_B$, $I_C = I_{C_{\text{majority}}} + I_{CO_{\text{minority}}}$, $I_C \cong I_E$, $V_{BE} = 0.7$ V, $\alpha_{dc} = I_C/I_E$, $I_C = \alpha I_E + I_{CBO}$, $\alpha_{ac} = \Delta I_C/\Delta I_E$, $I_{CEO} = I_{CBO}/(1 - \alpha)$, $\beta_{dc} = I_C/I_B$, $\beta_{ac} = \Delta I_C/\Delta I_B$, $\alpha = \beta/(\beta + 1)$, $\beta = \alpha/(1 - \alpha)$, $I_C = \beta I_B$, $I_E = (\beta + 1)I_B$, $P_{C_{\max}} = V_{CE}I_C$

4 DC Biasing—BJTs In general: $V_{BE} = 0.7$ V, $I_C \cong I_E$, $I_C = \beta I_B$; fixed-bias: $I_B = (V_{CC} - V_{BE})/R_B$, $V_{CE} = V_{CC} - I_C R_C$, $I_{C_{\text{sat}}} = V_{CC}/R_C$; emitter-stabilized: $I_B = (V_{CC} - V_{BE})/(R_B + (\beta + 1)R_E)$, $R_i = (\beta + 1)R_E$, $V_{CE} = V_{CC} - I_C(R_C + R_E)$, $I_{C_{\text{sat}}} = V_{CC}/(R_C + R_E)$; voltage-divider: exact: $R_{\text{Th}} = R_1 \| R_2$, $E_{\text{Th}} = R_2 V_{CC}/(R_1 + R_2)$, $I_B = (E_{\text{Th}} - V_{BE})/(R_{\text{Th}} + (\beta + 1)R_E)$, $V_{CE} = V_{CC} - I_C(R_C + R_E)$, approximate: $\beta R_E \geq 10R_2$, $V_B = R_2 V_{CC}/(R_1 + R_2)$, $V_E = V_B - V_{BE}$, $I_C \cong I_E = V_E/R_E$; voltage-feedback: $I_B = (V_{CC} - V_{BE})/(R_B + \beta(R_C + R_E))$; common-base: $I_B = (V_{EE} - V_{BE})/R_E$; switching transistors: $t_{\text{on}} = t_r + t_d$, $t_{\text{off}} = t_s + t_f$; stability: $S(I_{CO}) = \Delta I_C/\Delta I_{CO}$; fixed-bias: $S(I_{CO}) = \beta + 1$; emitter-bias: $S(I_{CO}) = (\beta + 1)(1 + R_B/R_E)/(1 + \beta + R_B/R_E)$; voltage-divider: $S(I_{CO}) = (\beta + 1)(1 + R_{\text{Th}}/R_E)/(1 + \beta + R_{\text{Th}}/R_E)$; feedback-bias: $S(I_{CO}) = (\beta + 1)(1 + R_B/R_C)/(1 + \beta + R_B/R_C)$, $S(V_{BE}) = \Delta I_C/\Delta V_{BE}$; fixed-bias: $S(V_{BE}) = -\beta/R_B$; emitter-bias: $S(V_{BE}) = -\beta/(R_B + (\beta + 1)R_E)$; voltage-divider: $S(V_{BE}) = -\beta/(R_{\text{Th}} + (\beta + 1)R_E)$; feedback bias: $S(V_{BE}) = -\beta/(R_B + (\beta + 1)R_C)$, $S(\beta) = \Delta I_C/\Delta\beta$; fixed-bias: $S(\beta) = I_{C_1}/\beta_1$; emitter-bias: $S(\beta) = I_{C_1}(1 + R_B/R_E)/(\beta_1(1 + \beta_2 + R_B/R_E))$; voltage-divider: $S(\beta) = I_{C_1}(1 + R_{\text{Th}}/R_E)/(\beta_1(1 + \beta_2 + R_{\text{Th}}/R_E))$; feedback-bias: $S(\beta) = I_{C_1}(1 + R_B/R_C)/(\beta_1(1 + \beta_2 + R_B/R_C))$, $\Delta I_C = S(I_{CO})\,\Delta I_{CO} + S(V_{BE})\,\Delta V_{BE} + S(\beta)\,\Delta\beta$

5 BJT AC Analysis $r_e = 26\text{ mV}/I_E$; CE fixed-bias: $Z_i \cong \beta r_e$, $Z_o \cong R_C$, $A_v = -R_C/r_e$; voltage-divider bias: $Z_i = R_1 \| R_2 \| \beta r_e$, $Z_o \cong R_C$, $A_v = -R_C/r_e$; CE emitter-bias: $Z_i \cong R_B \| \beta R_E$, $Z_o \cong R_C$, $A_v \cong -R_C/R_E$; emitter-follower: $Z_i \cong R_B \| \beta R_E$, $Z_o \cong r_e$, $A_v \cong 1$; common-base: $Z_i \cong R_E \| r_e$, $Z_o \cong R_C$, $A_v \cong R_C/r_e$; collector feedback: $Z_i \cong r_e/(1/\beta + R_C/R_F)$, $Z_o \cong R_C \| R_F$, $A_v = -R_C/r_e$; collector dc feedback: $Z_i \cong R_{F_1} \| \beta r_e$, $Z_o \cong R_C \| R_{F_2}$, $A_v = -(R_{F_2} \| R_C)/r_e$; effect of load impedance: $A_v = R_L A_{v_{\text{NL}}}/(R_L + R_o)$, $A_i = -A_v Z_i/R_L$; effect of source impedance: $V_i = R_i V_s/(R_i + R_s)$, $A_{v_s} = R_i A_{v_{\text{NL}}}/(R_i + R_s)$, $I_s = V_s/(R_s + R_i)$; combined effect of load and source impedance: $A_v = R_L A_{v_{\text{NL}}}/(R_L + R_o)$, $A_{v_s} = (R_i/(R_i + R_s))(R_L/(R_L + R_o))A_{v_{\text{NL}}}$, $A_i = -A_v R_i/R_L$, $A_{i_s} = -A_{v_s}(R_s + R_i)/R_L$; cascode connection: $A_v = A_{v_1}A_{v_2}$; Darlington connection: $\beta_D = \beta_1\beta_2$; emitter-follower configuration: $I_B = (V_{CC} - V_{BE})/(R_B + \beta_D R_E)$, $I_C \cong I_E \cong \beta_D I_B$, $Z_i = R_B \| \beta_1\beta_2 R_E$, $A_i = \beta_D R_B/(R_B + \beta_D R_E)$, $A_v \cong 1$, $Z_o = r_{e_1}/\beta_2 + r_{e_2}$; basic amplifier configuration: $Z_i = R_1 \| R_2 \| Z_i'$, $Z_i' = \beta_1(r_{e_1} + \beta_2 r_{e_2})$, $A_i = \beta_D(R_1 \| R_2)/(R_1 \| R_2 + Z_i')$, $A_v = \beta_D R_C/Z_i'$, $Z_o = R_C \| r_{o_2}$; feedback pair: $I_{B_1} = (V_{CC} - V_{BE_1})/(R_B + \beta_1\beta_2 R_C)$, $Z_i = R_B \| Z_i'$, $Z_i' = \beta_1 r_{e_1} + \beta_1\beta_2 R_C$, $A_i = -\beta_1\beta_2 R_B/(R_B + \beta_1\beta_2 R_C)$ $A_v = \beta_2 R_C/(r_e + \beta_2 R_C) \cong 1$, $Z_o \cong r_{e_1}/\beta_2$.

6 Field-Effect Transistors $I_G = 0$ A, $I_D = I_{DSS}(1 - V_{GS}/V_P)^2$, $I_D = I_S$, $V_{GS} = V_P(1 - \sqrt{I_D/I_{DSS}})$, $I_D = I_{DSS}/4$ (if $V_{GS} = V_P/2$), $I_D = I_{DSS}/2$ (if $V_{GS} \cong 0.3\,V_P$), $P_D = V_{DS}I_D$, $r_d = r_o/(1 - V_{GS}/V_P)^2$; MOSFET: $I_D = k(V_{GS} - V_T)^2$, $k = I_{D(\text{on})}/(V_{GS(\text{on})} - V_T)^2$

7 FET Biasing Fixed-bias: $V_{GS} = -V_{GG}$, $V_{DS} = V_{DD} - I_D R_D$; self-bias: $V_{GS} = -I_D R_S$, $V_{DS} = V_{DD} - I_D(R_S + R_D)$, $V_S = I_D R_S$; voltage-divider: $V_G = R_2 V_{DD}/(R_1 + R_2)$, $V_{GS} = V_G - I_D R_S$, $V_{DS} = V_{DD} - I_D(R_D + R_S)$; common-gate configuration: $V_{GS} = V_{SS} - I_D R_S$, $V_{DS} = V_{DD} + V_{SS} - I_D(R_D + R_S)$; special case: $V_{GS_Q} = 0\,V$: $I_{I_Q} = I_{DSS}$, $V_{DS} = V_{DD} - I_D R_D$, $V_D = V_{DS}$, $V_S = 0$ V. enhancement-type MOSFET: $I_D = k(V_{GS} - V_{GS(\text{Th})})^2$, $k = I_{D(\text{on})}/(V_{GS(\text{on})} - V_{GS(\text{Th})})^2$; feedback bias: $V_{DS} = V_{GS}$, $V_{GS} = V_{DD} - I_D R_D$; voltage-divider: $V_G = R_2 V_{DD}/(R_1 + R_2)$, $V_{GS} = V_G - I_D R_S$; universal curve: $m = |V_P|/I_{DSS}R_S$, $M = m \times V_G/|V_P|$, $V_G = R_2 V_{DD}/(R_1 + R_2)$

8 FET Amplifiers $g_m = y_{fs} = \Delta I_D/\Delta V_{GS}$, $g_{m0} = 2I_{DSS}/|V_P|$, $g_m = g_{m0}(1 - V_{GS}/V_P)$, $g_m = g_{m0}\sqrt{I_D/I_{DSS}}$, $r_d = 1/y_{os} = \Delta V_{DS}/\Delta I_D|_{V_{GS}=\text{constant}}$; fixed-bias: $Z_i = R_G$, $Z_o \cong R_D$, $A_v = -g_m R_D$; self-bias (bypassed R_S): $Z_i = R_G$, $Z_o \cong R_D$, $A_v = -g_m R_D$; self-bias (unbypassed R_S): $Z_i = R_G$, $Z_o = R_D$, $A_v \cong -g_m R_D/(1 + g_m R_s)$; voltage-divider bias: $Z_i = R_1 \| R_2$, $Z_o = R_D$, $A_v = -g_m R_D$; source follower: $Z_i = R_G$, $Z_o = R_S \| 1/g_m$, $A_v \cong g_m R_S/(1 + g_m R_S)$; common-gate: $Z_i = R_S \| 1/g_m$, $Z_o \cong R_D$, $A_v = g_m R_D$; enhancement-type MOSFETs: $g_m = 2k(V_{GS_Q} - V_{GS(\text{Th})})$; drain-feedback configuration: $Z_i \cong R_F/(1 + g_m R_D)$, $Z_o \cong R_D$, $A_v \cong -g_m R_D$; voltage-divider bias: $Z_i = R_1 \| R_2$, $Z_o \cong R_D$, $A_v \cong -g_m R_D$.

9 BJT and JFET Frequency Response $\log_e a = 2.3 \log_{10} a$, $\log_{10} 1 = 0$, $\log_{10} a/b = \log_{10} a - \log_{10} b$, $\log_{10} 1/b = -\log_{10} b$, $\log_{10} ab = \log_{10} a + \log_{10} b$, $G_{dB} = 10 \log_{10} P_2/P_1$, $G_{dBm} = 10 \log_{10} P_2/1\text{ mW}|_{600\,\Omega}$, $G_{dB} = 20 \log_{10} V_2/V_1$, $G_{dB_T} = G_{dB_1} + G_{dB_2} + \cdots + G_{dB_n}$ $P_{o_{HPF}} = 0.5 P_{o_{mid}}$, BW $= f_1 - f_2$; low frequency (BJT): $f_{L_S} = 1/2\pi(R_s + R_i)C_s$, $f_{L_C} = 1/2\pi(R_o + R_L)C_C$, $f_{L_E} = 1/2\pi R_e C_E$, $R_e = R_E \| (R_s'/\beta + r_e)$, $R_s' = R_s \| R_1 \| R_2$, FET: $f_{L_G} = 1/2\pi(R_{sig} + R_i)C_G$, $f_{L_C} = 1/2\pi(R_o + R_L)C_C$, $f_{L_S} = 1/2\pi R_{eq} C_S$, $R_{eq} = R_S \| 1/g_m (r_d \cong \infty\,\Omega)$; Miller effect: $C_{M_i} = (1 - A_v)C_f$, $C_{M_o} = (1 - 1/A_v)C_f$; high frequency (BJT): $f_{H_i} = 1/2\pi R_{Th_i} C_i$, $R_{Th_i} = R_s \| R_1 \| R_2 \| R_i$, $C_i = C_{w_i} + C_{be} + (1 - A_v)C_{bc}$, $f_{H_o} = 1/2\pi R_{Th_o} C_o$, $R_{Th_o} = R_C \| R_L \| r_o$, $C_o = C_{W_o} + C_{ce} + C_{M_o}$, $f_\beta \cong 1/2\pi\beta_{mid} r_e (C_{be} + C_{bc})$, $f_T = \beta_{mid} f_\beta$; FET: $f_{H_i} = 1/2\pi R_{Th_i} C_i$, $R_{Th_i} = R_{sig} \| R_G$, $C_i = C_{W_i} + C_{gs} + C_{M_i}$, $C_{M_i} = (1 - A_v)C_{gd}$ $f_{H_o} = 1/2\pi R_{Th_o} C_o$, $R_{Th_o} = R_D \| R_L \| r_d$, $C_o = C_{W_o} + C_{ds} + C_{M_o}$; $C_{M_o} = (1 - 1/A_v)C_{gd}$; multistage: $f_1' = f_1/\sqrt{2^{1/n} - 1}$, $f_2' = (\sqrt{2^{1/n} - 1})f_2$; square-wave testing: $f_{H_i} = 0.35/t_r$, % tilt $= P\% = ((V - V')/V) \times 100\%$, $f_{L_o} = (P/\pi)f_s$

10 Operational Amplifiers CMRR $= A_d/A_c$; CMRR(log) $= 20 \log_{10}(A_d/A_c)$; constant-gain multiplier: $V_o/V_1 = -R_f/R_1$; noninverting amplifier: $V_o/V_1 = 1 + R_f/R_1$; unity follower: $V_o = V_1$; summing amplifier: $V_o = -[(R_f/R_1)V_1 + (R_f/R_2)V_2 + (R_f/R_3)V_3]$; integrator: $v_o(t) = -(1/R_1C_1)\int v_1\,dt$

11 Op-Amp Applications Constant-gain multiplier: $A = -R_f/R_1$; noninverting: $A = 1 + R_f/R_1$: voltage summing: $V_o = -[(R_f/R_1)V_1 + (R_f/R_2)V_2 + (R_f/R_3)V_3]$; high-pass active filter: $f_{oL} = 1/2\pi R_1 C_1$; low-pass active filter: $f_{oH} = 1/2\pi R_1 C_1$

12 Power Amplifiers

Power in: $P_i = V_{CC} I_{CQ}$

power out: $P_o = V_{CE} I_C = I_C^2 R_C = V_{CE}^2/R_C$ rms

$= V_{CE} I_C/2 = (I_C^2/2)R_C = V_{CE}^2/(2R_C)$ peak

$= V_{CE} I_C/8 = (I_C^2/8)R_C = V_{CE}^2/(8R_C)$ peak-to-peak

efficiency: $\%\eta = (P_o/P_i) \times 100\%$; maximum efficiency: Class A, series-fed = 25%; Class A, transformer-coupled = 50%; Class B, push-pull = 78.5%; transformer relations: $V_2/V_1 = N_2/N_1 = I_1/I_2$, $R_2 = (N_2/N_1)^2 R_1$; power output: $P_o = [(V_{CE_{max}} - V_{CE_{min}})(I_{C_{max}} - I_{C_{min}})]/8$; class B power amplifier: $P_i = V_{CC}[(2/\pi)I_{peak}]$; $P_o = V_L^2(\text{peak})/(2R_L)$; $\%\eta = (\pi/4)[V_L(\text{peak})/V_{CC}] \times 100\%$; $P_Q = P_{2Q}/2 = (P_i - P_o)/2$; maximum $P_o = V_{CC}^2/2R_L$; maximum $P_i = 2V_{CC}^2/\pi R_L$; maximum $P_{2Q} = 2V_{CC}^2/\pi^2 R_L$; % total harmonic distortion (% THD) $= \sqrt{D_2^2 + D_3^2 + D_4^2 + \cdots} \times 100\%$; heat-sink: $T_J = P_D\theta_{JA} + T_A$, $\theta_{JA} = 40°\text{C/W}$ (free air); $P_D = (T_J - T_A)/(\theta_{JC} + \theta_{CS} + \theta_{SA})$

13 Linear-Digital ICs Ladder network: $V_o = [(D_0 \times 2^0 + D_1 \times 2^1 + D_2 \times 2^2 + \cdots + D_n \times 2^n)/2^n]V_{ref}$; 555 oscillator: $f = 1.44(R_A + 2R_B)C$; 555 monostable: $T_{high} = 1.1R_AC$; VCO: $f_o = (2/R_1C_1)[(V^+ - V_C)/V^+]$; phase-locked loop (PLL): $f_o = 0.3/R_1C_1$, $f_L = \pm 8f_o/V$, $f_C = \pm(1/2\pi)\sqrt{2\pi f_L/(3.6 \times 10^3)C_2}$

14 Feedback and Oscillator Circuits $A_f = A/(1 + \beta A)$; series feedback; $Z_{if} = Z_i(1 + \beta A)$; shunt feedback: $Z_{if} = Z_i/(1 + \beta A)$; voltage feedback: $Z_{of} = Z_o/(1 + \beta A)$; current feedback; $Z_{of} = Z_o(1 + \beta A)$; gain stability: $dA_f/A_f = 1/(|1 + \beta A|)(dA/A)$; oscillator; $\beta A = 1$; phase shift: $f = 1/2\pi RC\sqrt{6}$, $\beta = 1/29$, $A > 29$; FET phase shift: $|A| = g_m R_L$, $R_L = R_D r_d/(R_D + r_d)$; transistor phase shift: $f = (1/2\pi RC)[1/\sqrt{6 + 4(R_C/R)}]$, $h_{fe} > 23 + 29(R_C/R) + 4(R/R_C)$; Wien bridge: $R_3/R_4 = R_1/R_2 + C_2/C_1$, $f_o = 1/2\pi\sqrt{R_1C_1R_2C_2}$; tuned: $f_o = 1/2\pi\sqrt{LC_{eq}}$, $C_{eq} = C_1C_2/(C_1 + C_2)$, Hartley: $L_{eq} = L_1 + L_2 + 2M$, $f_o = 1/2\pi\sqrt{L_{eq}C}$

15 Power Supplies (Voltage Regulators) Filters: $r = V_r(\text{rms})/V_{dc} \times 100\%$, V.R. $= (V_{NL} - V_{FL})/V_{FL} \times 100\%$, $V_{dc} = V_m - V_r(\text{p-p})/2$, $V_r(\text{rms}) = V_r(\text{p-p})/2\sqrt{3}$, $V_r(\text{rms}) \cong (I_{dc}/4\sqrt{3})(V_{dc}/V_m)$; full-wave, light load $V_r(\text{rms}) = 2.4I_{dc}/C$, $V_{dc} = V_m - 4.17I_{dc}/C$, $r = (2.4I_{dc}CV_{dc}) \times 100\% = 2.4/R_LC \times 100\%$, $I_{peak} = T/T_1 \times I_{dc}$; RC filter: $V_{dc}' = R_L V_{dc}/(R + R_L)$, $X_C = 2.653/C$(half-wave), $X_C = 1.326/C$ (full-wave), $V_r'(\text{rms}) = (X_C/\sqrt{R^2 + X_C^2})$; regulators: $IR = (I_{NL} - I_{FL})/I_{FL} \times 100\%$, $V_L = V_Z(1 + R_1/R_2)$, $V_o = V_{ref}(1 + R_2/R_1) + I_{adj}R_2$

16 Other Two-Terminal Devices Varactor diode: $C_T = C(0)/(1 + |V_r/V_T|)^n$, $TC_C = (\Delta C/C_o(T_1 - T_0)) \times 100\%$; photodiode: $W = hf$, $\lambda = v/f$, 1 lm $= 1.496 \times 10^{-10}$ W, 1 Å $= 10^{-10}$ m, 1 fc $= 1$ lm/ft^2 $= 1.609 \times 10^{-9}$ W/m^2

17 *pnpn* and Other Devices Diac: $V_{BR_1} = V_{BR_2} \pm 0.1\, V_{BR_2}$ UJT: $R_{BB} = (R_{B_1} + R_{B_2})|_{I_E=0}$, $V_{R_{B_1}} = \eta V_{BB}|_{I_E=0}$, $\eta = R_{B_1}/(R_{B_1} + R_{B_2})|_{I_E=0}$, $V_P = \eta V_{BB} + V_D$; phototransistor: $I_C \cong h_{fe}I_\lambda$; PUT: $\eta = R_{B_1}/(R_{B_1} + R_{B_2})$, $V_P = \eta V_{BB} + V_D$