$$2 + 8 + 18 + 1 = 29$$

$$2 + 8 + 18 + 18 + 1 = 47$$

$$2 + 8 + 18 + 32 + 18 + 1 = 79$$

$$2n^2$$

Energy Level (n)	1	2	3	4	5	6
Shell Letter	K	L	M	N	O	P
Electron Capacity ($2n^2$)	2	8	18	32	50	72

$$2 + 8 + 4 = 14$$

$$2 + 8 + 18 + 4 = 32$$

I_0

$$I_D = I_0 \left(e^{V_D/\eta V_T} - 1 \right) \approx I_0 \, e^{V_D/\eta V_T},$$

$$V_D = \eta V_T \ ln\left(\frac{I_D}{I_0} + 1\right) \approx \eta V_T \ ln(I_D/I_0)$$

$V_D < 0$

V_D

$$10^{-10} \sim 10^{-12}$$

10^{-4}

$$V_T = kT/e$$

$$k = 1.38 \times 10^{-23}$$

$$e = 1.602 \times 10^{-19}$$

T

$$T = 300K$$

$27^\circ C$

$$V_T = kT/e = 26\ mV$$

η

$$I_D \approx -I_0$$

$$V_D = 0$$

$$I_D = 0$$

$V_D > 0$

$$I_D \approx I_0 e^{V_D/V_T}$$

I_D

I_D	$1\ mA$	$5\ mA$	$10\ mA$	$20\ mA$	$100\ mA$
V_D for Si ($I_0 = 10^{-10}, \eta = 1.4$)	$0.58V$	0.65	$0.67V$	0.7	$0.75V$
V_D for Ge ($I_0 = 10^{-4}, \eta = 1.0$)	$0.06V$	0.10	$0.12V$	0.14	$0.18V$

$$R = \Delta V / \Delta I$$

$V_D(I_D)$

$$R_D = dV_D/dI_D$$

$$R_D = \frac{d\,V_D}{d\,I_D} = \frac{d}{d\,I_D}\left[\eta V_T\ ln\left(\frac{I_D + I_0}{I_0}\right)\right] = \eta V_T \frac{I_0}{I_D + I_0}\frac{1}{I_0} = \eta\ \frac{V_T}{I_D + I_0} \approx \eta\ \frac{V_T}{I_D}$$

$$I_D \gg I_0$$

$$I_D + I_0 \approx I_D$$

$$V_T = 26\ mV$$

$\eta = 1.4$

I_D	$0.05\ mA$	$0.1\ mA$	$0.2\ mA$	$0.5\ mA$	$1\ mA$	$2\ mA$	$5\ mA$
R_D for Si ($\eta = 1.4$)	$728\,\Omega$	$364\,\Omega$	$182\,\Omega$	$73\,\Omega$	$36\,\Omega$	$18\,\Omega$	$7\,\Omega$

$$R_D = \infty$$

$$R_D = 0$$

$$I_D = V/R$$

$$V_0 = 0.7\,V$$

$$V_D < V_0$$

$$V_D = 0.7$$

$$I_D = (V - 0.7)/R$$

$$R_D = 20\Omega$$

$$I_D = (V - 0.7)/(R + R_D)$$

$$R = 1000\Omega$$

$$V = 3V$$

D

$$I_D = V/R = 3\ mA$$

$0.7V$

$$I_D = (V - 0.7)/R = 2.3/1000 = 2.3\ mA$$

$$V_0 = 0.7\ V$$

$$I_D = (3 - 0.7)/(1000 + 20) = 2.255\ mA$$

$$V_D = 0.7 + I_D R_D = 0.745\ V$$

$$\left\{ \begin{array}{l} I_D = I_0(e^{V_D/V_T} - 1) \\ V_D = V - RI_D \end{array} \right.$$

$$V_D = V - RI_0(e^{V_D/V_T} - 1)$$

$$I_D = I_0(e^{V_D/V_T} - 1)$$

$$V = V_D + I_D R$$

$$(V_D = 0, I_D = V/R)$$

$$(I_D = V, I_D = 0)$$

$$(V_D = 0.75\ V, I_D = 2.4\ mA)$$

$$R_L = 10\ K\Omega$$

$14.7\ V$

$$14.7/\sqrt{2} = 10.4V$$

$$115/10.4 = 11$$

$$I \approx V/R_L = 14/10 = 1.4\ mA$$

$$T = 1/f = 1/60 = 16.7\ ms$$

$$\Delta Q \approx IT = 1.4\ mA \times 16.7\ ms = 23.4\ \mu C$$

$$\Delta V = \Delta Q/C < 14 \times 5/\% = 0.7V$$

C

$$C = \Delta Q/\Delta V = 23.4\ \mu C/0.7V = 33.4\ \mu F$$

$$i(t) = \frac{V}{R_L} e^{-t/\tau}$$

V_{BE}

V_{CB}

E

B

I_B

I_C

I_E

$$I_C = I_E - I_B$$

α

$$\alpha = \frac{I_C}{I_E} < 1,$$

$$\alpha = 99\% \approx 1$$

I_C

$=$

αI_E

I_B

$$I_E - I_C = I_E - \alpha I_E = (1 - \alpha) I_E$$

$$I_E$$

$$\frac{I_C}{\alpha} = \frac{I_B}{1 - \alpha}$$

$$V_{CE}$$

$$I_E = f(V_{BE}, V_{CB}) \approx f(V_{BE}) = \frac{I_B}{1-\alpha} = \frac{1}{1-\alpha} I_0 (e^{V_{BE}/V_T} - 1)$$

$$I_B = I_0(e^{V_{BE}/V_T} - 1)$$

$$V_{BE} = 0.7\,V$$

$$I_C = f(I_E, V_{CB}) \approx f(I_E) = \alpha I_E$$

$$V_{CB} > 0.2V$$

$$V_{CB} > 0$$

$$I_E = 0$$

$$I_C = I_{CB0}$$

$$I_C = \alpha I_E + I_{CB0} \approx \alpha I_E$$

$$V_{CB} = 0$$

$I_C > 0$

$$V_{CE} > V_{BE}$$

$$V_{CE} = V_{CB} + V_{BE},$$

$$V_{CB} = V_{CE} - V_{BE}$$

β

$$\beta = \frac{I_C}{I_B} = \frac{\alpha I_E}{(1-\alpha)I_E} = \frac{\alpha}{1-\alpha},$$

$$\alpha = 0.99$$

$$\beta = 0.99/(1 - 0.99) = 99$$

$$\beta = \frac{\alpha}{1-\alpha}, \qquad \alpha = \frac{\beta}{1+\beta}, \qquad 1+\beta = \frac{1}{1-\alpha}, \qquad 1-\alpha = \frac{1}{1+\beta}$$

$$I_B = f(V_{BE}, V_{CE}) \approx f(V_{BE}) = I_0(e^{V_{BE}/V_T} - 1)$$

$$I_C = f(I_B, V_{CE}) \approx f(I_B) = \beta I_B$$

$$I_C = \beta I_B$$

$$I_E = I_C + I_B, \qquad V_{CE} = V_{CB} + V_{BE}$$

α

$$\frac{I_{out}}{I_{in}} = \frac{I_C}{I_E},$$

$$I_C = \alpha I_E$$

$$I_C + I_B = \alpha I_E + (1 - \alpha) I_E$$

β

$$\frac{I_{out}}{I_{in}} = \frac{I_C}{I_B},$$

$$I_C = \beta I_B$$

$$I_C + I_B = \beta I_B + I_B$$

$$I_C = \alpha I_E$$

$$I_C = 0$$

$$V_{CE} = 0$$

$$V_{CB} = -V_{BE}$$

$$\beta = \alpha/(1 - \alpha)$$

$\approx 0.3V$

$$V_{CE} > 0.3V$$

$$V_{CC} = 12V$$

$$R_B = 6K\Omega$$

$$R_C = 2K\Omega$$

$$\beta = 60$$

$$(V_{CE} = 0,\ I_C = V_{CC}/R_C = 6\ mA)$$

$$(I_C = 0,\ V_{CE} = V_{CC} = 12\ V)$$

$$V_{out} = V_{CE}$$

$$V_1$$

$$V_{BE} = V_{in} = 0 < 0.7V$$

$$I_B = 0$$

$$I_C = \beta I_B = 0$$

$$V_C = V_{CC} = 12\ V$$

$$V_{in} = 1V$$

$$V_{BE} \approx 0.7\ V$$

$$(V_{in} - V_{BE})/R_B = (1 - 0.7)/6 = 0.05\ mA$$

$$\beta I_B = 60 \times 0.05\ mA = 3\ mA$$

V_{CE}

$$V_{CC} - I_C R_C = 12\ V - 3\ mA \times 2\ K\Omega = 6\ V$$

$$V_{in} = 2V$$

$$I_B = (2 - 0.7)/6 = 0.22\ mA$$

$$I_C = \beta I_B = 13\ mA$$

$$V_{CE} = 12\ V - 13\ mA \times 2\ K\Omega = -14\ V$$

$$V_{CE} = 0.2V$$

$$(V_{CC} - V_{CE})/R_C = (12 - 0.2)/2 = 5.9\ mA$$

$$I_C = \beta\, I_B$$

$$V_{CC}/R_C$$

$< 0.2\,V$

$V_{BE} < 0.7V$

$$I_C = I_{CE0} \approx 0$$

$$V_C = V_{CC}$$

$$V_{BE} \approx 0.7V$$

$$I_B > 0$$

$$I_C = \beta I_B < V_{CC}/R_C$$

$$V_C = V_{CC} - R_C I_C$$

$$\beta I_B > V_{CC}/R_C$$

$$V_{CE} \approx 0.2V$$

$$I_E = I_B + I_C$$

$$V_{in} = V_{BE} = V_B$$

$$V_{out} = V_{CE} = V_C$$

V_{CC}

R_B

$$R_C$$

$$V_{CC} = 15V$$

$$R_C = 1.5K\ \Omega$$

$$\beta = 40$$

$$v_{in}(t) = v_{be}(t)$$

$$v_{be}(t) = 0.02 \ \cos(\omega t)\, V$$

$$V_{BE} + v_{be}(t) = 0.7 + 0.02\ \cos(\omega t)$$

$40\,mV$

$$V_{BE} = 0.7$$

$$r_{be} = \frac{\triangle v_{be}}{\triangle i_b} = \frac{40\,mV}{0.1\;mA} = 400\;\Omega$$

$$i_b(t)$$

$$I_B + i_b(t) \approx 0.1 + \frac{\triangle v_{be}}{r_{be}} = 0.1 + \frac{20\ \cos(\omega t)}{400} = (0.1 + 0.05\ \cos(\omega t))\ mA$$

$$I_B = 0.1\ mA$$

$0.05\ mA$

$$I_B + i_b(t) = \frac{V_{BE} + v_{be}(t)}{r_{be}} = \frac{0.7 + 0.02\ \cos(\omega t)}{400} = (1.75 + 0.05\ \cos(\omega t))\ mA$$

$$V_{CE} = V_{CC} - I_C R_C$$

$$\begin{cases} I_C = 0 \\ V_{CE} = V_{CC} = 15V \end{cases}$$

$$\begin{cases} V_{CE} = 0 \\ I_C = V_{CC}/R_C = 15V/1.5\,k\Omega = 10\,mA \end{cases}$$

$$I_C + i_c(t) = \beta(I_B + i_b(t)) = 40 \times (0.1 + 0.05\, cos(\omega t)) = (4 + 2\ \cos\ \omega t)\ mA$$

$$V_C + v_c(t) = V_{CC} - R_C(I_C + i_c(t)) = 15 - 1.5(4 + 2\ \cos(\omega t) = (9 - 3\ \cos(\omega t))\ V$$

$$0.02\ \cos(\omega t)\, V$$

$$-3\ \cos(\omega t)\, V$$

$$-3/0.02 = -150$$

$$-\cos\ \omega t$$

180°

$$\cos\ \omega t$$

$v_c(t)$

v_c

$$R_C = 1.5\ k\Omega$$

$$\beta = 50$$

$$V_1 = V_{BE} = 0.2V,\ 0.7V$$

$$0.8V$$

$$V_2 = V_{CE} = V_C$$

$$V_{BE} = 0.2V < 0.7V$$

$$V_2 = V_{CC} - I_C R_C = V_{CC} = 15V$$

$$V_{BE} = 0.7V$$

$0.1\ mA$

$$I_C = \beta I_B = 5\ mA$$

$$V_C = V_{CC} - I_C R_C = 15 - 5 \times 10^{-3} \times 1.5 \times 10^3 = 7.5\ V$$

$$V_{BE} = 0.8V > 0.7V$$

$0.4\ mA$

$$I_C = \beta I_B = 20\ mA$$

$$V_C = V_{CC} - I_C R_C = 15 - 20 \times 10^{-3} \times 1.5 \times 10^3 = -15V$$

$$I_C = 20\ mA$$

$$I_C = V_{CC}/R_C = 15\ V/1.5\ k\Omega = 10\ mA$$

$0.2V$

$$I_B = 0.4\ mA$$

$$I_C = (15 - 0.2)/1.5 \approx 10\ mA$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

$$I_C = \beta I_B = \beta \frac{V_{CC} - V_{BE}}{R_B}$$

$$V_{CE} = V_{CC} - I_C R_C$$

$$R_B = 200\,k\Omega$$

$$\beta = 100$$

$$V_{CC} = 12\,V$$

$$V_{CE} = V_{CC}/2 = 6\,V$$

$$V_{BE} = 0.6\ V$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B} = \frac{12 - 0.6}{200} = 0.057\,mA, \qquad I_C = \beta I_B = 5.7\,mA$$

$$I_C = 5.6\,mA$$

$$V_{CE} = V_{CC} - I_C R_C = 12 - 5.7 R_C = 6\,V,$$

$$R_C = \frac{6\,V}{5.6\,mA} \approx 1.05\,k\Omega$$

$$I_C = 5.7\, mA$$

$$\frac{V_{CC}}{R_C} = \frac{12\,V}{R_C} = 2 \times I_C = 11.4\ mA,$$

$$R_C = \frac{12\,V}{11.4\,mA} \approx 1.05\,k\Omega$$

$$V_{CE} = V_{CC} - R_C I_C = 12\,V - 1.05\,k\Omega \times 5.7\,mA \approx 6\,V$$

$$R_C = 1\,k\Omega$$

$$(V_{CE},\ I_C)$$

$$\beta = 50,\ 100,\ 200$$

$$V_C = V_{CC} - I_C R_C$$

$$I_C = 0,\ V_C = V_{CC} = 12\,V$$

$$V_C = 0,\ I_C = V_C/R_C = 12\,V/1\,k\Omega = 12\,mA$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B} = \frac{12 - 0.6}{200 \times 10^3} = 0.057\ mA$$

	$\beta = 50$	$\beta = 100$	$\beta = 200$
$I_C = \beta I_B$ (mA)	2.85	5.70	11.4
$V_C = V_{CC} - R_C I_C$ (V)	9.15	6.3	0.6

$$(V_C = 12/2 = 6\,V,\ I_C = 12/2 = 6\,mA)$$

$$\beta = 200$$

R_E

$$I_C \uparrow \Longrightarrow I_e = I_C + I_B \uparrow \Longrightarrow V_E \uparrow \Longrightarrow V_{BE} \downarrow \Longrightarrow I_B \downarrow \Longrightarrow I_C = \beta I_B \downarrow$$

R_1

R_2

I_2

$$I_2 \gg I_B$$

V_B

$$V_B = V_{CC}\ \frac{R_2}{R_1 + R_2}$$

$$V_B - V_{BE} - I_E R_E = V_B - V_{BE} - (I_C + I_B)R_E = V_B - V_{BE} - (\beta + 1)I_B R_E = 0$$

$$I_B = \frac{V_B - V_{BE}}{(\beta+1)R_E}, \qquad I_C = \beta I_B = \frac{\beta(V_B - V_{BE})}{(\beta+1)R_E} \approx \frac{V_B - V_{BE}}{R_E} = \frac{V_E}{R_E}$$

$$I_B \ll I_2$$

$$V_{Th} = V_B$$

$$R_{Th}$$

$$R_{Th} = R_B = R_1||R_2 = \frac{R_1 R_2}{R_1 + R_2}$$

$$V_B - I_B R_B - V_{BE} - (I_C + I_B) R_E = V_B - V_{BE} - I_B R_B - (\beta + 1) I_B R_E = 0$$

$$I_B = \frac{V_B - V_{BE}}{(\beta + 1)R_E + R_B},$$

$$I_C = \beta I_B = \frac{\beta(V_B - V_{BE})}{(\beta + 1)R_E + R_B}$$

$$R_B = R_1 || R_2$$

$$\beta R_E \gg R_B = R_1 || R_2$$

$$\beta R_E \geq 10 R_B$$

$$I_C \approx \frac{\beta(V_B - V_{BE})}{(\beta+1)R_E} \approx \frac{V_B - V_{BE}}{R_E} = \frac{V_E}{R_E}$$

$$I_C \approx \beta(V_{CC} - V_{BE})/R_B$$

$$R_1 = 100\,k\Omega$$

$$R_2 = 36\,k\Omega$$

$$R_E = 1\,k\Omega$$

$$R_C = 2\,k\Omega$$

$$V_{CE} = V_{CC} - I_C R_C - I_E R_E \approx V_{CC} - I_C(R_C + R_E)$$

$$I_C = V_{CC}/(R_C + R_E) = 12/(2+1) = 4\,mA$$

$$I_C = 0\,mA$$

$$V_{CE} = 12V$$

$$V_{CE} = 12\,V/2 = 6V$$

$$I_C = 4\,mA/2 = 2\,mA$$

R_B

$$R_1||R_2 = \frac{R_1 R_2}{R_1 + R_2} = 26.5\,k\Omega$$

V_B

$\approx$

$$V_{CC}\frac{R_2}{R_1 + R_2} = 3.18\ V$$

V_E

$$V_B - V_{BE} = 3.18 - 0.7 = 2.48\ V$$

$$I_E = \frac{V_E}{R_E} = 2.48\ mA$$

V_C

$$V_{CC} - R_C I_C = 12 - 2 \times 2.48 = 7.04\ V$$

$$V_C - V_E = 7.04 - 2.48 = 4.56\ V$$

$$\frac{V_B - V_{BE}}{(\beta + 1)R_E + R_B}$$

βI_B

$$I_E R_E = (I_C + I_B) R_E$$

$$V_E + V_{BE}$$

$$V_{CC} - I_C R_C$$

$$V_C - V_E$$

	$\beta = 50$	$\beta = 100$	$\beta = 200$
I_C (mA)	1.60	1.94	2.18
V_E (V)	1.63	1.96	2.19
V_C (V)	8.80	8.11	7.65
V_B (V)	2.33	2.66	2.89
V_{CE} (V)	7.17	6.15	5.46

$$I_C \approx 2\ mA$$

$$V_{CE} \approx 6\,V$$

$$R_1 = R_2 = 100\,k\Omega$$

$$R_E = 2\,k\Omega$$

$$R_{Th} = R_B = R_1 || R_2 = 50\ k\Omega, \qquad V_{Th} = V_B = V_{CC} \frac{R_2}{R_1 + R_2} = 6\, V$$

$$I_C = \beta I_B = \frac{\beta(V_B - V_{BE})}{(\beta+1)R_E + R_B} = \frac{100 \times (6-0.7)}{101 \times 2 + 50} = \frac{530}{250} = 2.12$$

$$V_{CE} = V_{CC} - (I_C + I_B)R_E - I_C R_C \approx V_{CC} - I_C(R_E + R_C) = 12 - 2.12 \times (2 + R_C)$$

$$V_{CE} = 12\,V/2 = 6\,V$$

$$R_C = 0.83\,k\Omega$$

V_C

$$I_C \uparrow \Longrightarrow V_C = V_{CC} - R_C I_C \downarrow \Longrightarrow I_B \downarrow \Longrightarrow I_C = \beta I_B \downarrow$$

$$V_{CC} = R_C(I_B + I_C) + R_B I_B + V_{BE} = (R_C(\beta + 1) + R_B)I_B + 0.7$$

$$I_B = \frac{V_{CC} - 0.7}{(\beta + 1)R_C + R_B}, \qquad I_C = \beta I_B = \frac{\beta(V_{CC} - 0.7)}{(\beta + 1)R_C + R_B}$$

$$V_C = V_{CC} - (I_C + I_B)R_C = V_{CC} - (\beta + 1)I_B R_C$$

$$R_B \ll (\beta + 1)R_C$$

$$I_C \approx (V_{CC} - 0.7)/R_C$$

$$V_{CC} = 10V$$

$$I_C = 2\,mA$$

$$I_C = 2mA$$

$$V_C = 5V$$

$$R_C = (V_{CC} - V_C)/I_C = 5V/2mA = 2.5K\Omega$$

$$I_B = I_C/\beta = 0.02mA, \qquad R_B = (5-0.7)/0.02 = 4.3/0.02 = 215K\Omega$$

$$I_C = \beta I_B, \qquad V_C = V_{CC} - I_E R_C = V_{CC} - (\beta + 1) I_B R_C$$

	$\beta = 50$	$\beta = 100$	$\beta = 200$
$I_B\ (mA)$	0.027	0.02	0.013
$I_C\ (mA)$	1.36	2	2.6
$V_C\ (V)$	6.6	5	3.5

$$v_1 = b_{be},\ i_1 = i_b,\ v_2 = v_{ce},\ i_2 = i_c$$

$$C_4^2 = 4!/[2!(4-2)!] = 6$$

$$\left\{\begin{array}{l} v_1 = f_1(i_1, i_2) \\ v_2 = f_2(i_1, i_2) \end{array}\right. \quad , \qquad \left\{\begin{array}{l} i_1 = f_3(v_1, v_2) \\ i_2 = f_4(v_1, v_2) \end{array}\right. \quad , \qquad \left\{\begin{array}{l} v_1 = f_5(i_1, v_2) \\ i_2 = f_6(i_1, v_2) \end{array}\right.$$

$$v_1 = v_{be}$$

$$i_1 = i_b$$

$$v_2 = v_{ce}$$

$$i_2 = i_{ce}$$

$$\begin{cases} v_{be} = v_{be}(i_b, v_{ce}) \\ i_c = i_c(i_b, v_{ce}) \end{cases}$$

$$dv_{be} = \frac{\partial v_{be}}{\partial i_b} di_b + \frac{\partial v_{be}}{\partial v_{ce}} dv_{ce} = h_i di_b + h_r dv_{ce} \qquad di_c = \frac{\partial i_c}{\partial i_b} di_b + \frac{\partial i_c}{\partial v_{ce}} dv_{ce} = h_f di_b + h_o dv_{ce}$$

h_i, h_f, h_r, h_o

$$h_i = \partial v_{be} / \partial i_b = r_{be}$$

$$v_{ce} = 0$$

$$h_r = \partial v_{be} / \partial v_{ce}$$

v_{ce}

v_{be}

$$i_b = 0$$

h_i

$$h_f = \partial i_c / \partial i_b = \beta$$

$$h_f = \beta$$

$$h_o = \partial i_c / \partial v_{ce} = 1/r_{ce}$$

$$h_o$$

i_b

i_c

$$\Delta x \to dx$$

Q

$$v_{be} = \frac{\partial v_{be}}{\partial i_b} i_b + \frac{\partial v_{be}}{\partial v_{ce}} v_{ce} = h_i i_b + h_r v_{ce} \approx h_i i_b \qquad i_c = \frac{\partial i_c}{\partial i_b} i_b + \frac{\partial i_c}{\partial v_{ce}} v_{ce} = h_f i_b + h_o v_{ce} \approx h_f i_b$$

$$h_r$$

$$h_i = r_{be}$$

$$h_f I_B = \beta I_B$$

r_{be}

$$h_i = r_{be} \approx \eta \frac{V_T}{I_B}$$

$$(V_T = 26\,mV)$$

$0.05 \sim 0.1mA$

βI_B

$$R_{in}$$

R_s

r_{out}

$$R_L$$

$$V_S$$

$$r_{in}$$

A

$$r_{in} = R_1||R_2||r_{be} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{r_{be}}\right)^{-1} = \frac{R_1R_2r_{be}}{R_1R_2 + R_1r_{be} + R_2r_{be}} \approx r_{be}$$

$$R_1,\ R_2 \gg r_{be}$$

$$r_{out} = R_C$$

v_{in}

$$v_b \approx v_{in} \; \frac{r_{be}}{r_{be} + R_s}, \qquad i_b = \frac{v_b}{r_{be}} \approx \frac{v_{in}}{r_{be} + R_s}$$

$$i_c = \beta i_b$$

$$v_{out} = v_c \approx -i_c\ (R_C||R_L) = -\beta\ i_b\ (R_C||R_L) = -\beta \frac{v_{in}}{r_{be} + R_s}(R_C||R_L)$$

v_b

$$A = \frac{v_{out}}{v_{in}} = \frac{v_c}{v_{in}} \approx -\beta \frac{R_C || R_L}{r_{be} + R_s}$$

$$R_s \ll r_{in} = R_1||R_2||r_{be} \approx r_{be}, \qquad R_L \gg r_{out} = R_C$$

$$A = \frac{v_{out}}{v_{in}} \approx -\beta \frac{R_C}{r_{be}}$$

$$r_{in} \approx r_{be}$$

$$r_{out} \approx R_C$$

$$r_{be} \approx \eta \, V_T / I_B$$

$$R_B = 300\,k\Omega$$

$$R_C = R_L = 4\,k\Omega$$

$$R_s = 0$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B} \approx \frac{V_{CC}}{R_B} = \frac{12}{300 \times 10^3} = 40 \times 10^{-6}\ A = 40\ \mu A$$

$$I_C = 0,$$

$$V_{CE} = 12V$$

$$V_{CE} = 0,$$

$$I_C = \frac{V_{CC}}{R_C} = \frac{12\ V}{4 \times 10^3\ \Omega} = 3 \times 10^{-3} A = 3\ mA$$

$$I_C = \beta I_B = 40 \times 40\ \mu A = 1.6\ mA, \qquad V_{CE} = V_{CC} - R_C I_C = 12 - 4 \times 1.6 = 5.6\ V$$

$$R'_L = R_C || R_L = 2\ k\Omega$$

$$1/R'_L = 1/2$$

$$\frac{1.5}{V_{AC0} - 6} = \frac{1}{2} \quad \Longrightarrow V_{AC0} = 8.8\,V$$

$$\frac{I_{AC0} - 1.5}{6} = \frac{1}{2} \quad \Longrightarrow I_{AC0} = 4.4\ mA$$

$$v_{in} = 20 \ \sin \ \omega t \ mV$$

$$V_{BE} = 0.6V$$

$$v_{be}(t) = V_{BE} + v_{in} = (0.6 + 0.02\ \sin\ \omega t)\ V$$

$$i_b(t) = I_B + i_{in} = (40 + 20\ \sin\ \omega t)\ \mu A$$

μA

$$r_{be} = \frac{\Delta v_{be}}{\Delta i_b} = \frac{20\,mV}{20\,\mu A} = 1\ k\Omega$$

$$i_c(t) = \beta\ i_b(t) = 40 \times (40 + 20 \sin \omega t)\ \mu A = (1.6 + 0.8\ \sin \omega t)\, mA$$

$$v_c(t) = V_{AC0} - R'_L \ i_c(t) = 8.8 - 2 \times (1.6 + 0.8 \ \sin \omega t) = (5.6 - 1.6 \ sin \ \omega t) \ V = v_{out}(t)$$

$$A_v = \frac{|v_{out}|}{|v_{in}|} = \frac{1.6}{0.02} = 80$$

$$r_{be} = 1\,k\Omega$$

$$(V_{CC} - V_{BE})/R_B \approx V_{CC}/R_B = 40\ \mu A$$

$$\beta \ I_B = 40 \times 40 \ \mu A = 1.6 \ mA$$

$$V_{CC} - R_C I_C = 12 - 1.6 \times 4 = 5.6\ V$$

$$i_b = v_{in}/r_{be}, \quad v_c = -i_c\ (R_C || R_L)$$

$$A_v = \frac{v_c}{v_{in}} = -\frac{\beta\ i_b\ (R_C||R_L)}{r_{be}\ i_b} = -\frac{\beta\,(R_C||R_L)}{r_{be}} = -\frac{(40 \times 2)\ k\Omega}{1\ k\Omega} = -80$$

$$r_{in} = R_B || r_{be} \approx r_{be} = 1\,k\Omega$$

$$r_{out} = R_C = 4\ k\Omega$$

$$R_S = 0$$

$$R_L = \infty$$

$$v_{in} = v_b, \quad v_{out} = v_c$$

$$\frac{v_c - v_s}{R_B} + \beta i_b + \frac{v_c}{R_C} = \frac{v_c - v_s}{R_B} + \beta \, \frac{v_s}{r_{be}} + \frac{v_c}{R_C} = 0$$

$$v_C \left(\frac{1}{R_B} + \frac{1}{R_C} \right) = v_s \left(\frac{1}{R_B} - \beta \frac{1}{r_{be}} \right)$$

A

$$\frac{v_{out}}{v_{in}} = \frac{v_c}{v_s} = \frac{1/R_B - \beta/r_{be}}{1/R_B + 1/R_C} = \frac{R_C(r_{be} - \beta R_B)}{(R_B + R_C)r_{be}} \approx -\beta \, \frac{R_C R_B}{(R_B + R_C)r_{be}}$$

$$-\beta \frac{R_B||R_C}{r_{be}} = -\beta \frac{R_C}{r_{be}} \frac{R_B}{R_B + R_C} \stackrel{R_B \to \infty}{\Longrightarrow} -\beta \frac{R_C}{r_{be}}$$

$$r_{be} \ll \beta R_B$$

$$R_B \to \infty$$

$$r'_{in}$$

$$i_b = v_b / r_{be} = v_s / r_{be}$$

βi_b

$\beta i_b R_C$

$$i = \frac{v_b - (-R_C \beta i_b)}{R_B + R_C} = \frac{v_b + R_C \beta v_b / r_{be}}{R_B + R_C} = v_b \frac{1 + R_C \beta / r_{be}}{R_B + R_C} \approx v_b \frac{\beta R_C / r_{be}}{R_B + R_C}$$

$$r_{be} \ll \beta R_C$$

$$r'_{in} = \frac{v_b}{i} = \frac{R_B + R_C}{\beta R_C / r_{be}} = \frac{R_B + R_C}{\beta R_C}\, r_{be}$$

$$r_{in} = r_{be}||r'_{in} = r_{be}\frac{1}{1+\beta R_C/(R_B+R_C)} = r_{be}\frac{R_B+R_C}{R_B+(\beta+1)R_C} = \begin{cases} r_{be} & R_B \to \infty \\ r_{be}/\beta & R_B \to 0 \end{cases}$$

$$v_{oc} = A v_b = -\beta \frac{R_C}{r_{be}} \frac{1}{1 + R_C/R_B} \, v_b$$

$$R_L = 0$$

$$i' = v_b / R_B$$

$$i'' = -\beta i_b = -\beta v_b / r_{be}$$

$$i_{sc} = i' + i'' = v_b \left(\frac{1}{R_B} - \frac{\beta}{r_{be}} \right)$$

r_{out}

$$\frac{v_{oc}}{i_{sc}} = \frac{-\beta \frac{R_C}{r_{be}} \frac{1}{1+R_C/R_B}}{1/R_B - \beta/r_{be}} = \frac{-\beta \frac{R_C}{r_{be}} \frac{1}{1+R_C/R_B}}{\frac{r_{be}-\beta R_B}{R_B r_{be}}}$$

$$\frac{-\beta \frac{R_C}{r_{be}} \frac{R_B}{R_B+R_C}}{\frac{-\beta R_B}{R_B r_{be}}} = \frac{R_C R_B}{R_C + R_B} = R_C || R_B \overset{R_B \to \infty}{\Longrightarrow} R_C$$

$$V_{CC} - V_{BE} = I_B R_B + (\beta + 1) I_B R_E, \qquad I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1) R_E}$$

$$I_C = \beta I_B = \beta \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E}, \qquad V_{CE} \approx V_{CC} - I_C(R_C + R_E)$$

$$V_{CC} = 12V,\ R_E = 0.1\,k\Omega,\ \beta = 100$$

$$R_C = 1.9\,k\Omega$$

$$I_E = \frac{V_{CC} - V_{CE}}{R_C + R_E} = \frac{6}{0.1 + 1.9} = 3\,mA, \quad I_B = \frac{I_C}{\beta} = 0.03\,mA$$

$$R_B + (\beta + 1)R_E = \frac{V_{CC} - V_{BE}}{I_B} = \frac{12 - 0.7}{0.03} = 377\,k\Omega$$

$$R_B = 377 - 100 \times 0.1 = 367\,k\Omega$$

$$R_B = 250\,k\Omega$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + \beta R_E} = \frac{12 - 0.7}{250 + 100 \times 0.1} = \frac{11.3}{260} = 0.044$$

$$\frac{V_{CC} - V_{CE}}{R_C + R_E} = \frac{6}{0.1 + R_C} = I_C = \beta I_B = 4.4\,mA$$

$$R_C = 1.26\,k\Omega$$

$$i_b + \beta i_b = (\beta + 1) i_b = \frac{v_e}{R_E} = \frac{v_{in} - r_{be} i_b}{R_E}$$

$$i_b = \frac{v_{in}}{r_{be} + (\beta + 1)R_E}$$

$$r_{in} = \frac{v_{in}}{i_{in}} = \frac{v_{in}}{i_b} = r_{be} + (\beta + 1)R_E \approx \beta R_E$$

$$A = \frac{v_{out}}{v_{in}} = -\frac{\beta i_b (R_C||R_L)}{v_{in}} = -\frac{\beta\,(R_C||R_L)}{v_{in}} \frac{v_{in}}{r_{be} + (\beta+1)R_E} = -\frac{\beta\,R_C||R_L}{r_{be} + (\beta+1)R_E} \approx -\frac{R_C||R_L}{R_E}$$

$$v_{oc} = -\beta i_b R_C$$

$$i_{sc} = -\beta i_b$$

$$r_{out} = \frac{v_{oc}}{i_{sc}} = R_C$$

$$v_{out} = v_e \uparrow \Longrightarrow v_{be} \downarrow \Longrightarrow i_b \downarrow \Longrightarrow i_c \downarrow \Longrightarrow v_e \downarrow$$

$$V_{CC} = R_B I_B + V_{BE} + R_E I_E = R_B I_B + V_{BE} + R_E(\beta + 1) I_B$$

$$I_B = \frac{V_{CC} - V_{BE}}{(\beta + 1)R_E + R_B}$$

$$I_E = (\beta + 1)I_B = \frac{(\beta + 1)(V_{CC} - V_{BE})}{(\beta + 1)R_E + R_B}$$

$$V_{CE} = V_{CC} - V_E = V_{CC} - R_E I_E$$

$$R_B = 100\,k\Omega$$

$$V_{CC} = 10\,V$$

$$V_{CE} = V_{CC} - V_E = 10 - V_E = V_{CC}/2 = 5\,V$$

$$V_E = 5\,V$$

$$V_E = I_E R_E = R_E \, \frac{(\beta+1)(V_{CC} - V_{BE})}{(\beta+1)R_E + R_B} = \frac{101 \; R_E(10 - 0.7)}{101 \; R_E + 100} = 5 \, V$$

$$R_E = 1.15\,k\Omega$$

$$I_B = \frac{V_{CC} - V_{BE}}{(\beta + 1)R_E + R_B} = 0.043\,mA, \qquad I_C = \beta\,I_B = 100\,I_B = 4.3\,mA$$

$$I_E = (\beta + 1)I_B = 4.34\,mA, \quad V_E = I_E R_E = 5\,V$$

R_S

R_{be}

$$\begin{cases} v_{out} = v_e = (R_E||R_L)i_e = (R_E||R_L)(i_c + i_b) = (R_E||R_L)(\beta+1)i_b \\ v_{in} = (R_s + r_{be})i_b + v_{out} = (R_s + r_{be})i_b + (R_E||R_L)(\beta+1)i_b \end{cases}$$

$$A = \frac{v_{out}}{v_{in}} = \frac{(\beta+1)(R_E||R_L)}{(R_s + r_{be}) + (\beta+1)(R_E||R_L)} \approx 1$$

$$R_s + r_{be} \ll (\beta + 1)(R_E || R_L)$$

$$v_b = i_b r_{be} + v_{out} = i_b \left[r_{be} + (\beta + 1)(R_E || R_L) \right]$$

$$r'_{in} = \frac{v_b}{i_b} = r_{be} + (\beta + 1)(R_E || R_L) \approx r_{be} + \beta(R_E || R_L) \approx \beta(R_E || R_L)$$

$$r_{in} = R_B || r'_{in} \approx r'_{in} \approx \beta(R_E || R_L)$$

$$r_{in} = R_1||R_2||r_{be} \approx r_{be}$$

r'_{out}

v_{OC}

$$i_{sc}$$

$$v_{oc} \approx v_{in}$$

$$i_{sc} = i_e = (\beta + 1)i_b = (\beta + 1)\frac{v_{in}}{r_{be} + R_s} \approx \beta\frac{v_{in}}{r_{be} + R_s}$$

$$r'_{out} = \frac{v_{oc}}{i_{sc}} \approx \frac{r_{be} + R_s}{\beta}$$

$$r_{out} = R_E || r'_{out} = R_E || \left(\frac{r_{be} + R_s}{\beta} \right) \approx \frac{r_{be} + R_s}{\beta}$$

$$v_{out} = v_e$$

$$r_{in} = \beta \left(R_E || R_L \right)$$

$$r_{out} = (r_{be} + R_s)/\beta$$

$$R_E || R_L$$

$$R_s + r_{be}$$

$$R_{in} = \beta R_E$$

$$R_{out} = r_{be}/beta$$

$$r_{in} = r_{be}$$

R_{out}

$$\triangle V = V_1 - V_2$$

V_2

T_1

$$T_2$$

$$I_E = I_1 + I_2$$

I_1

$$V_1 = V_2$$

$$\Delta V = V_1 - V_2 = 0$$

$$I_1 = I_2 = I_E/2$$

$$V_{out} = V_{CC} - I_2 R_C$$

$$\Delta V = 0$$

$$V_1 > V_2$$

$$V_1 \uparrow \Longrightarrow I_1 \uparrow \Longrightarrow I_2 \downarrow \Longrightarrow V_{out} = V_{CC} - I_2 R_c \uparrow$$

$$V_1 < V_2$$

$$V_1 \downarrow \Longrightarrow I_1 \downarrow \Longrightarrow I_2 \uparrow \Longrightarrow V_{out} = V_{CC} - I_2 R_c \downarrow$$

V_{out}

$$0.7 \times 3 = 2.1V$$

$$I_L = I_{ce}$$

I_L

$$Q_1$$

Q_2

$$\beta_1 = \beta_2 = \beta$$

I_{ref}

$$I_{ref} = \frac{V_{CC} - V_B}{R_C}$$

$$\beta \gg 1$$

$$I_{ref} = I_C + 2I_B = I_C(1 + 2/\beta) \approx I_C$$

$$V_B = V_C$$

$$I_B = I_C/\beta$$

$$V_B = V_T \ln\left(\frac{I_B}{I_0} + 1\right) \approx V_T \ \ln\left(\frac{I_B}{I_0}\right)$$

V_T

$$V_B \uparrow \Longrightarrow I_B \uparrow \Longrightarrow (I_C = \beta I_B) \uparrow \Longrightarrow (V_C = V_B = V_{CC} - I_C R_C) \downarrow$$

$$V_B = V_{C1}$$

$$I_{C1} \approx I_{ref} = (V_{CC} - V_B)/R_C$$

I_{B2}

$$I_{C2} = \beta I_{B2} = I_L$$

$$V_{B2} = V_{B1} = V_B$$

$$I_{B2} = I_{B1} = I_B$$

$$I_{C2} = \beta I_B = I_{C1} = I_C$$

$$I_L = I_C = I_{ref}/(1 + 2/\beta) \approx I_{ref} = \frac{V_{CC} - V_B}{R_C}$$

I_{C2}

$$I_L = I_{C3}$$

$$(I_L = I_{C3}) \uparrow \Longrightarrow I_{C2} \uparrow \Longrightarrow I_{C1} \uparrow \Longrightarrow (V_{C1} = V_{B3}) \downarrow \Longrightarrow I_{B3} \downarrow \Longrightarrow (I_L = I_{C3}) \downarrow$$

$$\theta = 360^\circ$$

$$\theta = 180^\circ$$

$\theta < 180^\circ$

$$\omega_0 = 1/\sqrt{LC}$$

Z_c

L

L_1

L_2

$$\omega_0 = 1/\sqrt{C(L_1 + L_2)}$$

C_1

C_2

$$\omega_0 = 1/\sqrt{LC_1C_2/(C_1 + C_2)}$$

$$v_c = v_{out}$$

$$v_{feedback} = v_c \frac{Z_{L_1}}{Z_{L_1} + Z_{L_2}} = v_c \frac{L_1}{L_1 + L_2}, \qquad v_{feedback} = v_c \frac{Z_{C_2}}{Z_{C_2} + Z_{C_3}} = v_c \frac{C_3}{C_2 + C_3}$$

$$v_c \uparrow \Longrightarrow v_{feedback} \uparrow \Longrightarrow v_e \uparrow \Longrightarrow v_{be} \downarrow \Longrightarrow i_b \downarrow \Longrightarrow i_c \downarrow \Longrightarrow v_c \uparrow$$

ω_{RF}

$$\omega_{IF}$$

$\omega_{IF} = 455$

$$\omega_{IF} = 10.7$$

$$i_c = \beta i_b = \beta\, I_o \left(e^{v_{be}/V_T} - 1\right)$$

$$e^x = \sum_{k=0}^{\infty} \frac{x^k}{k!},$$

$$e^x - 1 = x + \frac{1}{2}x^2 + \frac{1}{3!}x^3 + \cdots \approx x + \frac{1}{2}x^2$$

$$v_{be} = \cos(\omega_1 t) + \cos(\omega_2 t)$$

i_c

$\propto$

$$(\cos\omega_1 t + \cos\omega_2 t) + \frac{1}{2}(\cos\omega_1 t + \cos\omega_2 t)^2 + \cdots$$

$$\cos\omega_1 t + \cos\omega_2 t + \frac{1}{2}\left(\cos^2\omega_1 t + 2\cos\omega_1 t\ \cos\omega_2 t + \cos^2\omega_2 t\right)$$

$$\cos\omega_1 t + \cos\omega_2 t + \frac{1}{4}(1 + \cos(2\omega_1 t)) + \frac{1}{2}\cos(\omega_1 + \omega_2)t + \frac{1}{2}\cos(\omega_1 - \omega_2)t + \frac{1}{4}(1 + \cos(2\omega_2 t))$$

$$\cos^2\alpha = \frac{1+\cos 2\alpha}{2}, \qquad \cos\alpha\ \cos\beta = \frac{\cos(\alpha+\beta)+\cos(\alpha-\beta)}{2}$$

ω_1

$$\omega_2$$

$$\omega_1 + \omega_2$$

$$\omega_1 - \omega_2$$

$2\omega_1$

$$2\omega_2$$

ω_{OS}

$$\Delta\omega = \omega_{OS} - \omega_{RF} = \omega_{IF}$$

$$G(j\omega)$$

$$F(j\omega)$$

V_o

$$V_i = 0$$

V_i

$$V_o = G(V_i + FV_o) = GV_i + GFV_o, \qquad \frac{V_o}{V_i} = H = \frac{G}{1 - GF}, \qquad V_o = HV_i = \frac{G}{1 - GF}\, V_i$$

GF

H

$$\angle(GF) = 0$$

$$|GF| = 1$$

$$\omega_0 = \frac{1}{\sqrt{LC_s}},$$

$$C_s = \left(\frac{1}{C_1} + \frac{1}{C_2} \right)^{-1}$$

$$C_s$$

$$\omega_0 = 1/\sqrt{LC_s}$$

$$v_c \uparrow \Longrightarrow v_e \uparrow \Longrightarrow v_{be} \downarrow \Longrightarrow i_b \downarrow \Longrightarrow i_c = \beta i_b \downarrow \Longrightarrow v_c \uparrow$$

$$v_{C_1} = v_b$$

$$v_{C_2} = v_c$$

$$v_c \uparrow \Longrightarrow v_b \downarrow \Longrightarrow v_{be} \downarrow \Longrightarrow i_b \downarrow \Longrightarrow i_c = \beta i_b \downarrow \Longrightarrow v_c \uparrow$$

v_e

$$v_e = v_t \uparrow \Longrightarrow v_b \uparrow \Longrightarrow i_b \uparrow \Longrightarrow i_e = (\beta + 1) i_b \uparrow \Longrightarrow v_e \uparrow$$

v_t

$$H = V_o/V_i$$

R

V_t

$$\frac{V_t - V_i}{R} + \frac{V_t}{1/j\omega C_2} + \frac{V_t}{j\omega L + 1/j\omega C_1} = 0$$

$$V_t \left(\frac{1}{R} + j\omega C_2 + \frac{j\omega C_1}{1 - \omega^2 L C_1} \right) = \frac{V_i}{R}$$

$$V_t = \frac{1}{R(\frac{1}{R} + j\omega C_2 + \frac{j\omega C_1}{1-\omega^2 LC_1})} \; V_i = \frac{1}{1 + j\omega R(C_2 + C_1/(1-\omega^2 LC_1)} \; V_i$$

$$C_2 + \frac{C_1}{1 - \omega_0^2 L C_1} = 0,$$

$$\omega_0 = \frac{1}{\sqrt{LC_1C_2/(C_1+C_2)}} = \frac{1}{\sqrt{LC_s}}$$

ω_0

$$V_t = V_i$$

Z_{tank}

$$Z_{C_2} || (Z_{C_1} + Z_L) = \frac{Z_{C_2}(Z_{C_2} + Z_L)}{Z_{C_2} + Z_{C_1} + Z_L} = \frac{(1/j\omega C_1 + j\omega L)/j\omega C_2}{1/j\omega C_2 + 1/j\omega C_1 + j\omega L}$$

$$\frac{(1/j\omega C_1 + j\omega L)/C_2}{1/C_1 + 1/C_2 - \omega^2 L} = \frac{(1/j\omega C_1 + j\omega L)/C_2}{1/C_s - \omega^2 L} \overset{\omega=\omega_0}{\Longrightarrow} \infty$$

$$\omega = \omega_0$$

$$Z_{tank} = \infty$$

$$V_t = \frac{Z_{C_2}}{Z_{C_1} + Z_{C_2}} \; V_o = \frac{C_1}{C_1 + C_2} \, V_o,$$

$$V_o = \frac{C_1 + C_2}{C_1}\ V_t = \frac{C_1 + C_2}{C_1}\ V_i$$

$$H = \frac{V_o}{V_i} = \frac{C_1 + C_2}{C_1}$$

HG

SiO_2

$$V_{GS} = V_G - V_S > 0$$

$$V_{DS} = V_D - V_S > 0$$

V_{GS}

$$\begin{cases} V_{GS} \uparrow \Longrightarrow I_D \uparrow \Longrightarrow \text{conducting} \\ V_{GS} \downarrow \Longrightarrow I_D \downarrow \Longrightarrow \text{cut off} \end{cases}$$

$$I_D = \begin{cases} 0 & \text{if } V_{GS} < V_T \text{ (cutoff)} \\ K(V_{GS} - V_T)^2 & \text{if } V_{GS} \geq V_T \text{ (conducting)} \end{cases}$$

V_{DS}

$$I_D(V_{GS}, V_{DS})$$

$$I_C = f(I_B,\, V_{CE})$$

$$V_{GS} < V_T$$

$$V_{GS} > V_T$$

$$V_{GD} = V_{GS} - V_{DS} > V_T$$

V_{GD}

$$\Delta V_{DS}/\Delta I_D$$

$$V_{GS} > V_{GD}$$

$$V_{GD} = V_{GS} - V_{DS} < V_T$$

$$V_{GD} = V_{GS} - V_{DS} = V_T$$

$$V_T = 1V$$

$$V_{GS} < V_T = 1V$$

$$V_{GS} = 2V > V_T = 1V$$

$$V_{DS} < V_{GS} - V_T = 1V$$

$$V_{DS} > V_{GS} - V_T = 1V$$

$$K = 2mA/V^2$$

V

$$V_{GS} = 2V$$

$3V$

$$r_{in} > 10^{11}\Omega$$

$$V_{in} = V_{GS} > V_T$$

$$V_{DS} > V_{in} - V_T$$

$$\left\{ \begin{array}{l} I_D = K(V_{in} - V_T)^2 \\ V_{out} = V_{DS} = V_{dd} - I_D R = V_{dd} - KR(V_{in} - V_T)^2 \end{array} \right.$$

$$V_{in}$$

$$V_{DS} = V_{out} = V_{dd} - KR(V_{in} - V_T)^2 \geq V_{in} - V_T$$

$$V_{in} - V_T$$

$$V_{in} - V_T < \frac{-1 + \sqrt{1 + 4KRV_{dd}}}{2KR},$$

$$V_{in} < \frac{-1 + \sqrt{1 + 4KRV_{dd}}}{2KR} + V_T$$

$$V_{in} > V_T$$

$$V_T < V_{in} < \frac{-1 + \sqrt{1 + 4KRV_{dd}}}{2KR} + V_T$$

$$0 < V_{in} - V_T < \frac{-1 + \sqrt{1 + 4KRV_{dd}}}{2KR}$$

$$g = \frac{dV_{out}}{dV_{in}} = \frac{d}{dV_{in}}(V_{dd} - KR(V_{in} - V_T)^2) = -2KR(V_{in} - V_T)$$

$$V_{dd} = 10V$$

$$R = 10k\Omega$$

$$K = 0.5\ mA/V^2$$

$$V_{in} > V_T = 1\ V$$

$$V_{in} < [-1 + \sqrt{1 + 4KRV_{dd}}\ ]/2KR + V_T = 2.32\ V$$

$$V_{out} = V_{dd} - K(V_{in} - V_T)^2 R = 10 - 5(V_{in} - 1)^2$$

$$g(V_{in}) = \frac{d}{d\,V_{in}} V_{out}(V_{in}) = -10(V_{in} - 1)$$

$1.8V$

$1.9V$

$6.8V$

$6V$

$$g(V_{in}) = g(1.8) = -10(1.8 - 1) = -8$$

$2.0V$

$2.1V$

$5V$

$4V$

$$g(V_{in}) = g(2) = -10(2-1) = -10$$

$$V_T = 1V < V_{in} < 2.32V$$

$$|g| > 1$$

$g < 0$

$$V_{out}(V_{in})$$

$$V_{in} < V_T = 1V$$

$$V_{in} > 2.32V$$

$$V_{in} = 2.32$$

$$V_{out} = 1.3 < V_{in} - V_T = 2.32 - 1 = 1.32$$

$$R = 10\ k\Omega$$

$$K = 1\ mA/V^2$$

$$V_{dd} = 5V$$

$$v_{in}(t) = V_{bias} + \sin(\omega t)$$

$$V_{bias} = 1.5V$$

$v_{in}(t)$

$$v_{out} = V_{dd} - RI_D = V_{dd} - RK(V_{in} - V_T)^2 = 5 - 10(V_{in} - 1)^2$$

$$V_{in} = 1.4V,\ 1.5V,\ 1.6V$$

v_{out}

i_{DS}

$$v_{out} = 3.4V,\ 2.5V,\ 1.4V$$

$$i_{DS} = 0.16mA,\ 0.25mA,\ 0.36mA$$

$$V_{bias} = V_{dd} \frac{R_1}{R_1 + R_2}$$

$$R_1 = 84k$$

$$R_2 = 16k$$

$$R_d = 20k$$

$$K = 0.5mA/V^2$$

$$V_B = V_{bias} = 1.6V$$

$$V_{GS} = V_B - V_{in}$$

$$V_{out} = V_{dd} - R_d K (V_{GS} - V_T)^2 = V_{dd} - R_d K (V_B - V_{in} - V_T)^2 = 10 - 10 \times (0.6 - V_{in})^2$$

$$V_{in} = 0$$

$$V_{out} = 6.4V$$

$$V_{GS} - V_T \geq 0$$

$$V_{GS} - V_T = V_B - V_{in} - V_T = 0.6 - V_{in} \geq 0$$

$$V_{in} \leq 0.6V$$

$$V_{out} < 10V$$

$$V_{DS} \geq V_{GS} - V_T$$

$$V_{DS} = V_{out} - V_{in} = (V_{dd} - R_d I_D) - V_{in} = V_{dd} - R_d K (V_B - V_{in} - V_T)^2 - V_{in} \geq V_B - V_{in} - V_T$$

$$V_{out} = V_{dd} - R_d K (V_B - V_{in} - V_T)^2 \geq V_B - V_T$$

$$V_{out} = 10 - 10 \times (0.6 - V_{in})^2 \geq 0.6$$

$$V_{in} \geq -0.37V$$

$$V_{out} \geq 0.6V$$

$$-0.37V \leq V_{in} \leq 0.6V$$

$$0.6V \leq V_{out} \leq 10V$$

$$g = 9.7$$

$$R_s = 10k\Omega$$

$$K = 10mA/V^2$$

$$I_D = V_{out}/R_s$$

$$I_D = K(V_{GS} - V_T)^2 = K(V_{in} - V_{out} - V_T)^2 = V_{out}/R_s$$

$$(V_{in} - V_{out} - 1)^2 = V_{out}$$

$$(V_{out} - 1)^2 = V_{out}$$

$$V_{out} = 2.6V$$

$$V_{out} = 0.4V$$

$$V_{GS} = V_{in} - V_{out} = 2 - V_{out} > V_T = 1$$

$$V_{in} = 3V$$

$$(V_{out} - 2)^2 = V_{out}$$

$$V_{out} = 1V$$

$$g = \frac{\Delta V_{out}}{\Delta V_{in}} = \frac{1 - 0.4}{3 - 2} = 0.6 < 1$$

$$\{V_{GS}, I_D, V_{DS}\}$$

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}}$$

g_m

S

V_{gs}

G

$$V_{gs} > V_{Tn}$$

$$V_{Tn} = 1\ V$$

$$V_{gs} \leq V_{Tp}$$

$$V_{Tp} = -1\ V$$

$$f(a, b, \cdots, x)$$

V_s

$$f = TRUE$$

$$f = FALSE$$

f'

f

$$f(a, b, c) = (a' + b')c$$

$$f'(a,b,c) = [(a'+b')c]' = (a'+b')' + c' = ab + c'$$

$$f(V_1, V_2) = (V_1 V_2)' = V_1' + V_2'$$

$$f' = V_1 \; V_2$$

$$(V_1\ V_2)' = V_1' + V_2'$$

$$V_{out} = f(V_1, V_2) = V_1' + V_2' = (V_1 V_2)'$$

$$f(V_1 + V_2) = (V_1 + V_2)' = V_1' \, V_2'$$

$$f' = V_1 + V_2$$

$$(V_1 + V_2)' = V_1' \, V_2'$$

$$V_{out} = (V_1 + V_2)'$$

		AND	OR	NAND	NOR
V_1	V_2	$V_1\ V_2$	$V_1 + V_2$	$(V_1\ V_2)'$	$(V_1 + V_2)'$
0	0	0	0	1	1
0	1	0	1	1	0
1	0	0	1	1	0
1	1	1	1	0	0

$$f'(a, b, c) = ab + c'$$