APPENDIX

The following information may be used where applicable:

Elementary charge	q	= 1.602 x 10^{-19} C
Permittivity of free space	ε_0	= 8.854 x 10^{-14} F cm^{-1}
Room temperature		= 300 K
Thermal voltage at 300 K	V_T	= kT/q = 0.025 V = 25 mV
Intrinsic carrier concentration of silicon at 300 K	n_i	= 1.5 x 10^{10} cm^{-3}
Relative permittivity of silicon	$\varepsilon_{r,}$ (Si)	= 11.7
Relative permittivity of silicon dioxide	$\varepsilon_{r,}$ (SiO_2)	= 3.9

Summary of Equations

I. Semiconductor Physics

Quantity	**Equation**	**Remarks**
Law of mass action	$p_0 n_0 = n_i^2$	$n_i = 1.5 \times 10^{10}$ cm^{-3} for Si at T = 300 K
Charge neutrality	$p + N_D = n + N_A$	
Carrier concentrations in p-type semi-conductor at thermal equilibrium (cm^{-3})	$p_{p0} = N_A$ $n_{p0} = \dfrac{n_i^2}{N_A}$	T = 300 K N_A = net p-type doping concentration
Carrier concentrations in n-type semi-conductor at thermal equilibrium (cm^{-3})	$n_{n0} = N_D$ $p_{n0} = \dfrac{n_i^2}{N_D}$	T = 300 K N_D = net n-type doping concentration
Drift current density (A cm^{-2})	$J_{drift} = J_{p,drift} + J_{n,drif}$ $J_{p,drift} = qp\mu_p E$ $J_{n,drift} = qn\mu_n E$ $J_{drift} = q(p\mu_p + n\mu_n)E = \sigma E$	σ is conductivity, E is electric field
Conductivity (Ω cm)$^{-1}$	$\sigma = q(p\mu_p + n\mu_n) = \dfrac{1}{\rho}$	ρ is resistivity
Diffusion current density (A cm^{-2})	$J_{diff} = J_{p,diff} + J_{n,diff}$ $J_{p,diff} = -qD_p \dfrac{dp}{dx}$ $J_{n,diff} = qD_n \dfrac{dn}{dx}$ $J_{diff} = -qD_p \dfrac{dp}{dx} + qD_n \dfrac{dn}{dx}$	
Einstein Relation	$\dfrac{D_p}{\mu_p} = \dfrac{D_n}{\mu_n} = \dfrac{kT}{q} = V_T$	$k = 1.381 \times 10^{-23}$ J/K $= 8.62 \times 10^{-5}$ eV/K $q = 1.602 \times 10^{-19}$ C $V_T \approx 0.025$ V at T = 300 K.

II. pn Junction

Quantity	Equation	Remarks
Junction built-in voltage (V)	$V_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$	$V_0 \cong 0.6$ - 0.8 V for Si at $T = 300$ K. N_D is the doping concentration of the *n*-region. N_A is the doping concentration of the *p*-region.
Width of depletion region (cm or µm)	$W_{dep} = x_p + x_n$ $= \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_A} + \frac{1}{N_D}\right](V_0 - V)}$ $x_p = \frac{N_D}{N_D + N_A} W_{dep}$, $x_n = \frac{N_A}{N_D + N_A} W_{dep}$	V is positive for forward bias and negative for reverse bias $\varepsilon_s = 11.7 \times \varepsilon_0$ for Si $\varepsilon_0 = 8.854 \times 10^{-14}$ F cm^{-1}. x_p is the depletion width in the *p*-region. x_n is the depletion width in the *n*-region.
Minority carrier concentration at the edge of depletion region (cm^{-3})	*p*-side: $n_p(-x_p) = n_{p0}\, e^{V/V_T}$ *n*-side: $p_n(x_n) = p_{n0}\, e^{V/V_T}$	= thermal equilibrium minority carrier concentration x e^{V/V_T}
Minority carrier concentration distributions in the neutral n- and p-regions (cm^{-3})	*n*-side : $p_n(x) = p_{n0} + [p_n(x_n) - p_{n0}]\, e^{-(x-x_n)/L_p}$ *p*-side : $n_p(x) = n_{p0} + [n_p(-x_p) - n_{p0}]\, e^{(x+x_p)/L_n}$	L_p, L_n are the diffusion lengths of the minority carriers in the *n*-side and *p*-side respectively. In the equations, $x > x_n$ on the *n*-side, and $x < -x_p$ on the *p*-side.
Current (A)	$I = I_p + I_n = I_s\left(e^{V/nV_T} - 1\right)$ $I_p = Aqn_i^2 \frac{D_p}{L_p N_D}\left(e^{V/nV_T} - 1\right)$ $I_n = Aqn_i^2 \frac{D_n}{L_n N_A}\left(e^{V/nV_T} - 1\right)$	*n* is a value between 1 and 2. I_P is the hole current injected into the neutral *n*-region. I_n is the electron current injected into the neutral *p*-region.
Saturation current (A)	$I_S = Aqn_i^2\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right)$	
Amount of charge stored in (one side) of the depletion region (C)	$q_j = qx_p N_A A = qx_n N_D A$ $= q\left(\frac{N_A N_D}{N_A + N_D}\right) W_{dep} A$	
Depletion or junction capacitance (F)	$C_j = \frac{\varepsilon_s A}{W_{dep}}$	*m* is a value the ranges between 1/3 to 1/2.

	$$C_j = A\left[\frac{q\varepsilon_s}{2}\left(\frac{N_A N_D}{N_A+N_D}\right)\frac{1}{(V_0-V)}\right]^m$$ $$C_j = A\times C_{j0}/\left(1-\frac{V}{V_0}\right)^m$$ $$C_{j0} = \left[\frac{q\varepsilon_s}{2}\left(\frac{N_A N_D}{N_A+N_D}\right)\frac{1}{V_0}\right]^m$$	
Small signal (or incremental) resistance of the pn junction diode (Ω)	$r_d = \frac{nV_T}{I_D}$	I_D is the (d.c.) diode current at the operating point, n is a value between 1 and 2.

III. Bipolar Junction Transistor (BJT)

Quantity	**Equation**	**Remarks**
Magnitude of the diffusion current of the minority carriers (electrons) in the base of an npn BJT (A)	$\lvert i_{En}\rvert = \left\lvert qAD_n \frac{n_p(0)-n_p(w_B)}{0-w_B}\right\rvert$	D_n is the diffusivity of the electrons in the base, w_B is the width of the neutral part of the base, $n_p(0)$ and $n_p(w_B)$ are the concentrations of the electrons on the base side of the edges of the E-B and C-B space charge regions respectively.
Collector current of an npn BJT (A)	$i_C = I_S \exp\left(\frac{v_{BE}}{V_T}\right)$	
Collector saturation current of an npn BJT (A)	$I_S = qA\frac{D_n}{w_B}\frac{n_i^2}{N_{AB}}$	Note that the symbol I_S is also the symbol for the saturation current of a p-n junction diode, but the expression is different.
Base current of an npn BJT (A)	$i_B = \frac{I_S}{\beta}\exp\left(\frac{v_{BE}}{V_T}\right)$ where $\beta = \frac{D_n}{D_p}\frac{L_p}{w_B}\frac{N_{DE}}{N_{AB}}$	The expression for β here is for an npn BJT with a long emitter.
Common emitter current gain of a BJT (general definition)	$\beta = \frac{i_C}{i_B}$	
Common base current gain of a BJT (general definition)	$\alpha = \frac{i_C}{i_E}$	
Relationship between α and β	$\beta = \frac{\alpha}{1-\alpha}$	
Collector current of an npn BJT, with Early effect taken into account (A)	$i_C = I_S \exp\left(\frac{v_{BE}}{V_T}\right)\left(1+\frac{v_{CE}}{V_A}\right)$	V_A is the Early voltage.

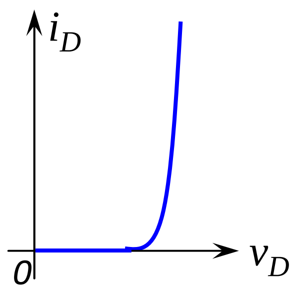
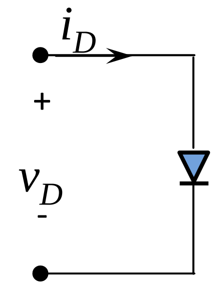
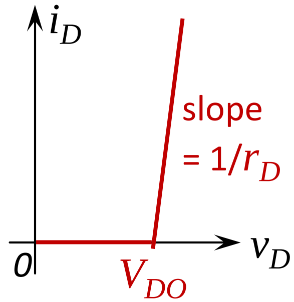
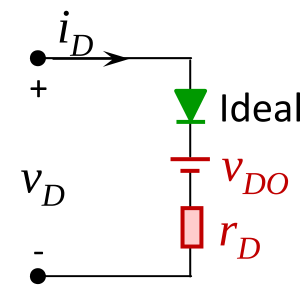
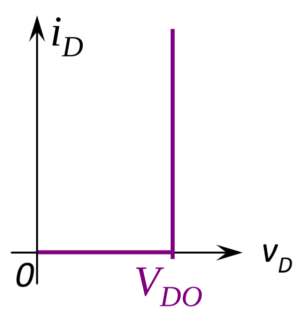
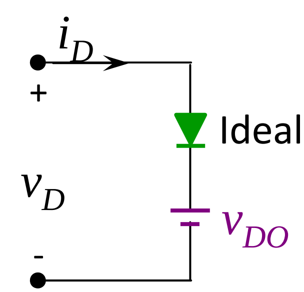
Transconductance in the small signal equivalent circuit of a BJT (Ω^{-1})	$g_m = \left.\dfrac{I_C}{V_T}\right\|_{\text{at bias point}}$	I_C is the value of the collector current at the d.c. operating (bias) point.
Input resistance in the small signal equivalent circuit of a BJT (Ω)	$r_\pi = \dfrac{\beta}{g_m}$	
Output resistance in the small signal equivalent circuit of a BJT (Ω)	$r_o \approx \dfrac{V_A}{I_C}$	I_C is the value of the collector current at the d.c. operating (bias) point.

IV. Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

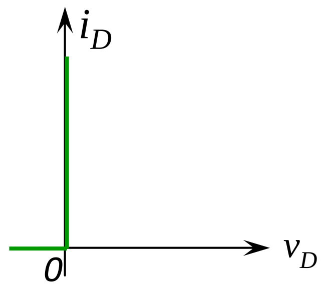
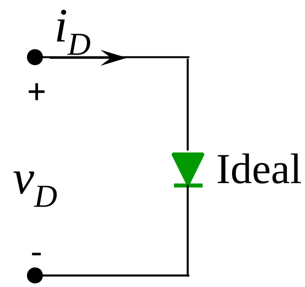
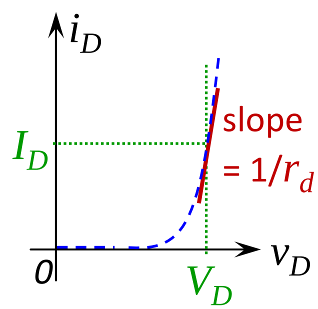
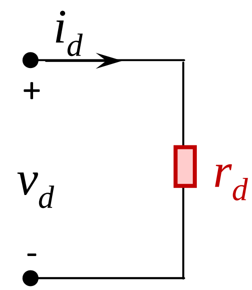
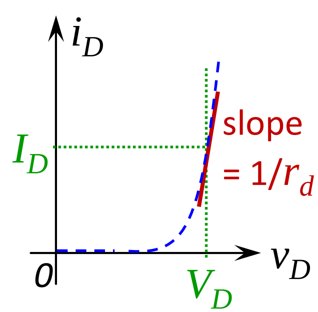
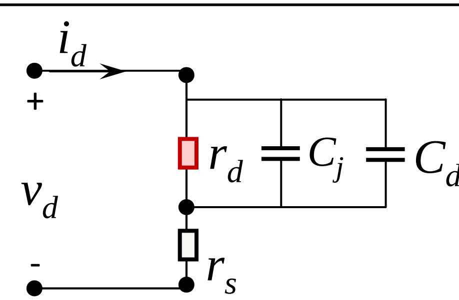
<u>**Quantity**</u>	<u>**Equation**</u>	<u>**Remarks**</u>
Drain current of an n-MOSFET operating in the linear region	$i_D = \mu_n \dfrac{W}{L} C_{ox}\left[(v_{GS} - V_{TH})\, v_{DS} - \dfrac{1}{2} v_{DS}^2\right]$ $= 2K_n\left[(v_{GS} - V_{TH})\, v_{DS} - \dfrac{1}{2} v_{DS}^2\right]$	Valid for $v_{DS} \le v_{GS} - V_{TH}$
Drain current of an n-MOSFET operating in the saturation region	$i_D = i_{Dsat} = \dfrac{1}{2}\mu_n \dfrac{W}{L} C_{ox}(v_{GS} - V_{TH})^2$ $= K_n(v_{GS} - V_{TH})^2$	Valid for $v_{DS} \ge v_{GS} - V_{TH}$
Transconductance parameter of an n-MOSFET	$K_n = \dfrac{1}{2}\mu_n \dfrac{W}{L} C_{ox}$	
Drain current of a p-MOSFET operating in the linear region	$\|i_D\| = \mu_p \dfrac{W}{L} C_{ox}\left[(\|v_{GS}\| - \|V_{TH}\|)\, \|v_{DS}\| - \dfrac{1}{2}\|v_{DS}\|^2\right]$ $= 2K_p\left[(\|v_{GS}\| - \|V_{TH}\|)\, \|v_{DS}\| - \dfrac{1}{2}\|v_{DS}\|^2\right]$	Valid for $\|v_{DS}\| \le \|v_{GS}\| - \|V_{TH}\|$
Drain current of a p-MOSFET operating in the saturation region	$\|i_D\| = \|i_{Dsat}\| = \dfrac{1}{2}\mu_p \dfrac{W}{L} C_{ox}(\|v_{GS}\| - \|V_{TH}\|)^2$ $= K_p(\|v_{GS}\| - \|V_{TH}\|)^2$	Valid for $\|v_{DS}\| \ge \|v_{GS}\| - \|V_{TH}\|$
Transconductance parameter of a p-MOSFET	$K_p = \dfrac{1}{2}\mu_p \dfrac{W}{L} C_{ox}$	
Gate oxide capacitance (per unit gate area) of a MOSFET	$C_{ox} = \dfrac{\varepsilon_{ox}}{t_{ox}}$	
Transconductance in the small signal equivalent circuit of an n-MOSFET operating in the saturation region	$g_m = 2K_n(V_{GS} - V_{TH}) = 2\sqrt{K_n I_D}$	I_D and V_{GS} are the magnitudes of the drain current and gate-to-source voltage, respectively, at the d.c. operating point.

Transconductance in the small signal equivalent circuit of a p-MOSFET operating in the saturation region	$g_m = 2K_p(\lvert V_{GS}\rvert - \lvert V_{TH}\rvert) = 2\sqrt{K_p\lvert I_D\rvert}$	I_D and V_{GS} are the magnitudes of the drain current and gate-to-source voltage, respectively, at the d.c. operating point.
Drain-to-source resistance in the large signal model of the n-MOSFET operating in the linear region	$R_{DS} = \dfrac{1}{2K_n(V_{GS} - V_{TH})}$	V_{GS} is the magnitude of the gate-to-source voltage, at the d.c. operating point.
Drain-to-source resistance in the large signal model of the p-MOSFET operating in the linear region	$R_{DS} = \dfrac{1}{2K_p(\lvert V_{GS}\rvert - \lvert V_{TH}\rvert)}$	V_{GS} is the magnitude of the gate-to-source voltage, at the d.c. operating point.
Output resistance in the small signal equivalent circuit of a MOSFET operating in the saturation region	$r_o \approx \dfrac{V_A}{I_D} = \dfrac{1}{\lambda I_D}$	I_D is the magnitude of the drain current at the d.c. operating point.
Drain current of an n-MOSFET operating in the saturation region, including channel length modulation effect	$i_D = K_n(v_{GS} - V_{TH})^2(1 + \lambda v_{DS})$	Valid for $v_{DS} \geq v_{GS} - V_{TH}$
Drain current of an p-MOSFET operating in the saturation region, including channel length modulation effect	$\lvert i_D\rvert = K_p(\lvert v_{GS}\rvert - \lvert V_{TH}\rvert)^2(1 + \lambda\lvert v_{DS}\rvert)$	Valid for $\lvert v_{DS}\rvert \geq \lvert v_{GS}\rvert - \lvert V_{TH}\rvert$

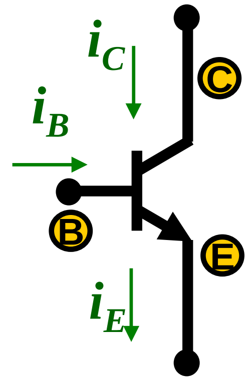
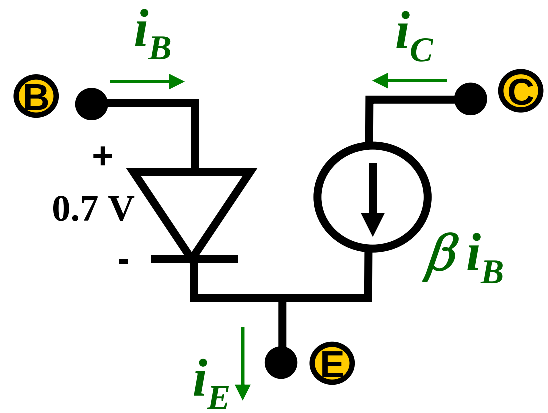
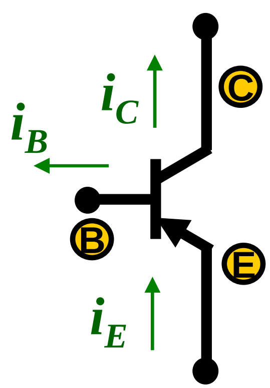
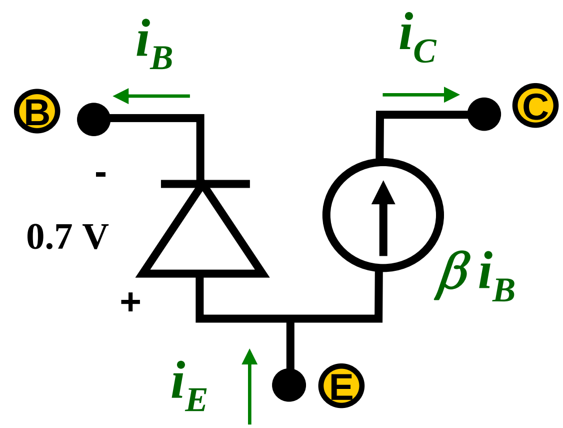
Summary of *pn* junction models (Forward Bias)

Model	Graph	Equations	Circuit	Comments
Exponential		$i_D \cong I_S e^{\frac{v_D}{nV_T}}$ $v_D = nV_T \ln(i_D / I_S)$ $v_{D2} - v_{D1} = nV_T \ln(i_{D2} / i_{D1})$		**Physically based and accurate model. Useful for accurate analysis.**
Piece-wise linear		For $v_D \leq V_{DO}$: $i_D = 0$ For $v_D \geq V_{DO}$: $i_D = (v_D - V_{DO}) / r_D$		**Choice of V_{DO} and r_D is determined by current range over which model is used.**
Constant-voltage drop		For $v_D \leq V_{DO}$: $i_D = 0$ For $v_D \geq V_{DO}$: $i_D = V_{DO}$		**Easy to use model and very popular for quick analysis.** **Typically V_{DO} = 0.7 V.**

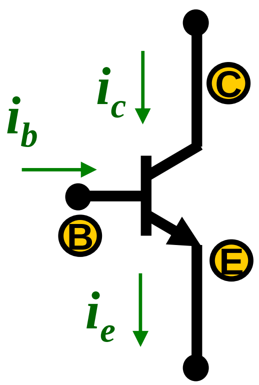
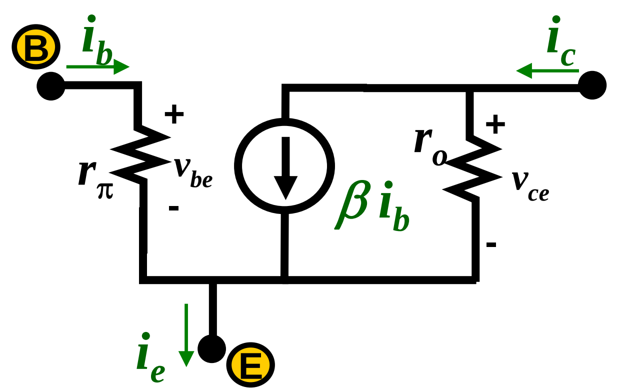
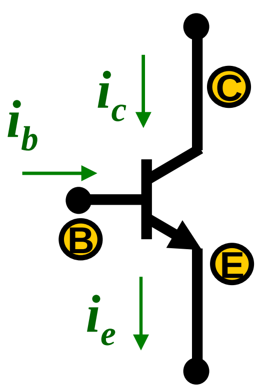
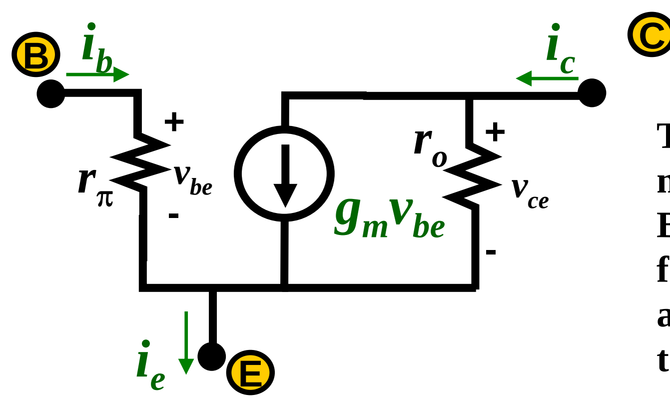
Summary of *pn* junction models (Forward Bias)

Model	Graph	Equations	Circuit	Comments
Ideal-diode		For $v_D < 0:$ $i_D = 0.$ For $v_D = 0:$ $i_D > 0.$		
Small-signal		Around dc biasing (I_D,V_D), small-signal i_d and v_d : $i_d \cong v_d / r_d$ $r_d = nV_T / I_D$		**For analysis of small-signal superimposed on dc biasing point (I_D,V_D)**
Small-signal (with capacitive & series resistance effects)				

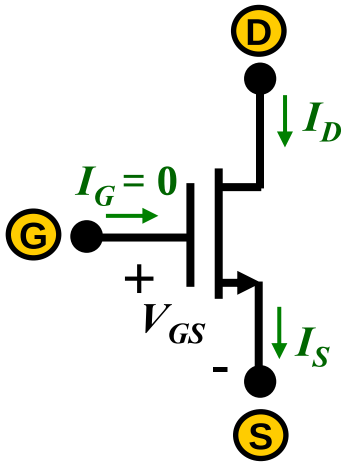
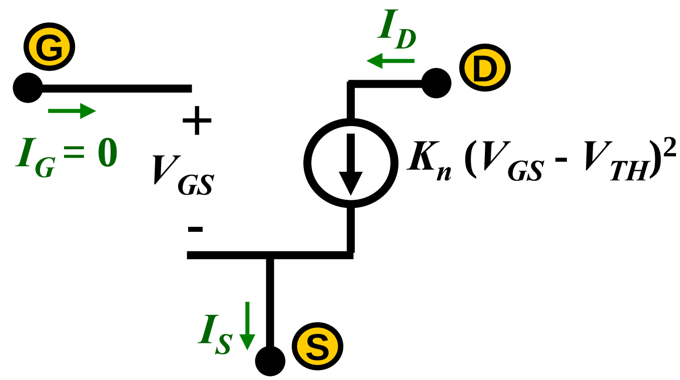
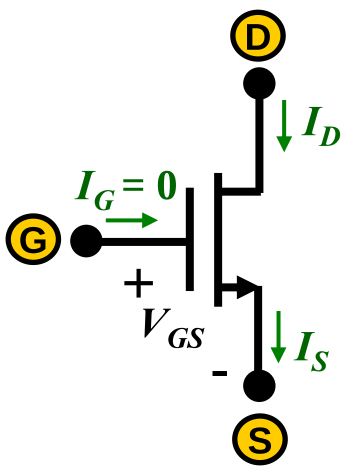
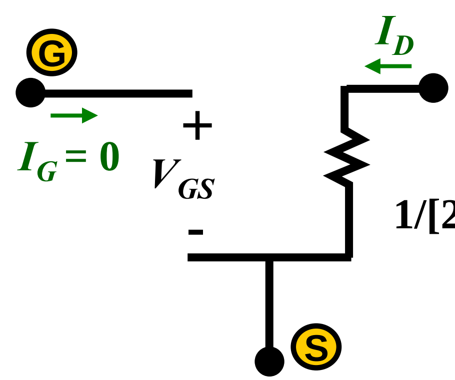
Summary of *BJT* models

Model	Circuit Symbol	Equations	Circuit	Comments
Large signal model of the **npn** BJT		$i_C = I_S e^{v_{BE}/V_T}$ $i_C = \beta\, i_B$		
Large signal model of the **pnp** BJT		$i_C = I_S e^{v_{EB}/V_T}$ $i_C = \beta\, i_B$		

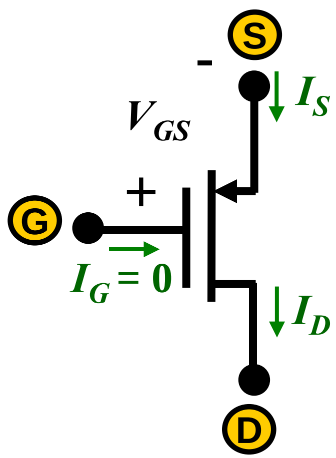
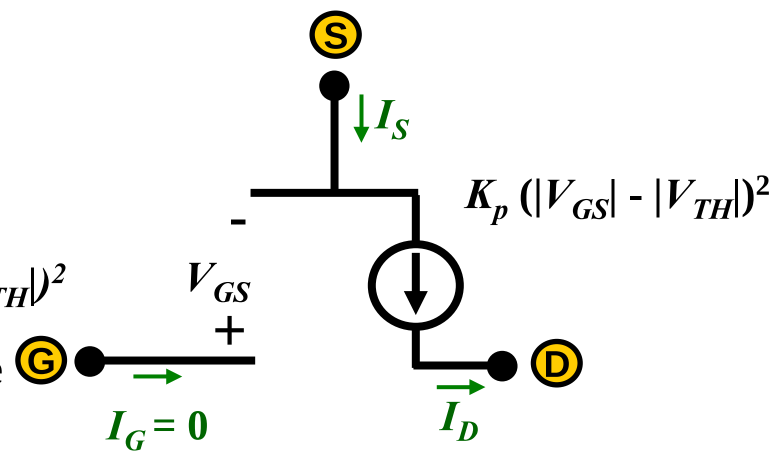
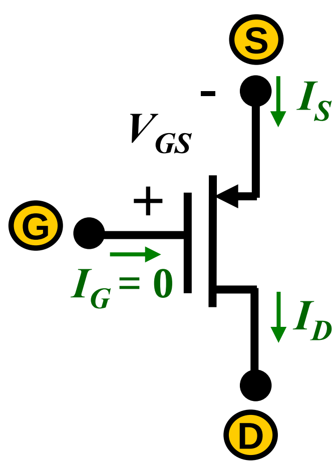
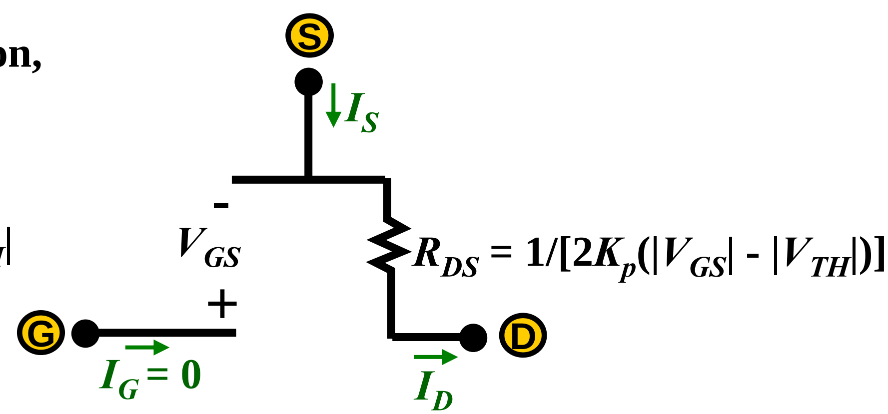
Summary of *BJT* models

Model	Circuit Symbol	Equations	Circuit	Comments
Small signal (or hybrid-π) model of the BJT (current-controlled version)		$g_m = \frac{I_C}{V_T}$ $r_\pi = \frac{\beta}{g_m}$ $r_o = \frac{V_A}{I_C}$		**I_C is the collector current at the d.c. bias point. V_T is the thermal voltage and V_A is the Early voltage.**
Small signal (or hybrid-π) model of the BJT (voltage-controlled version)				**The small signal model of the BJT is the same for both npn and pnp transistors.**

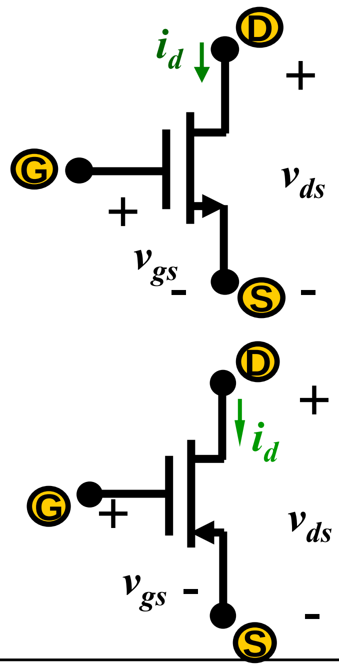
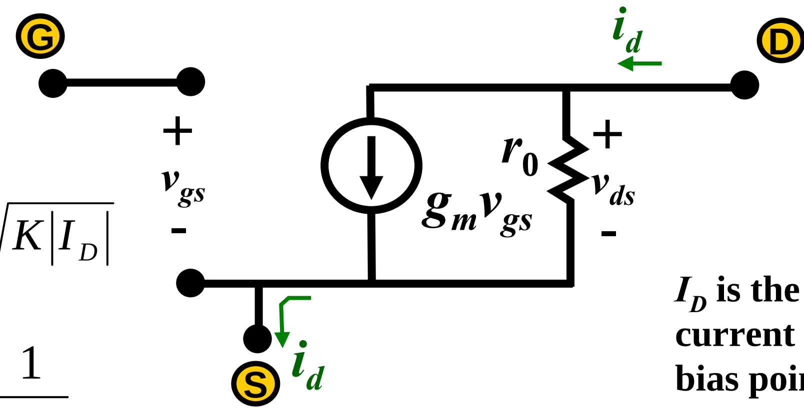
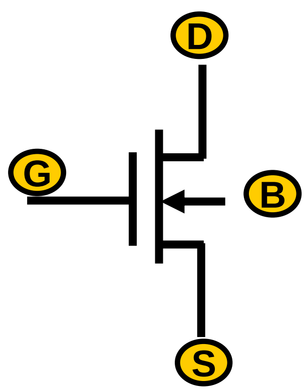
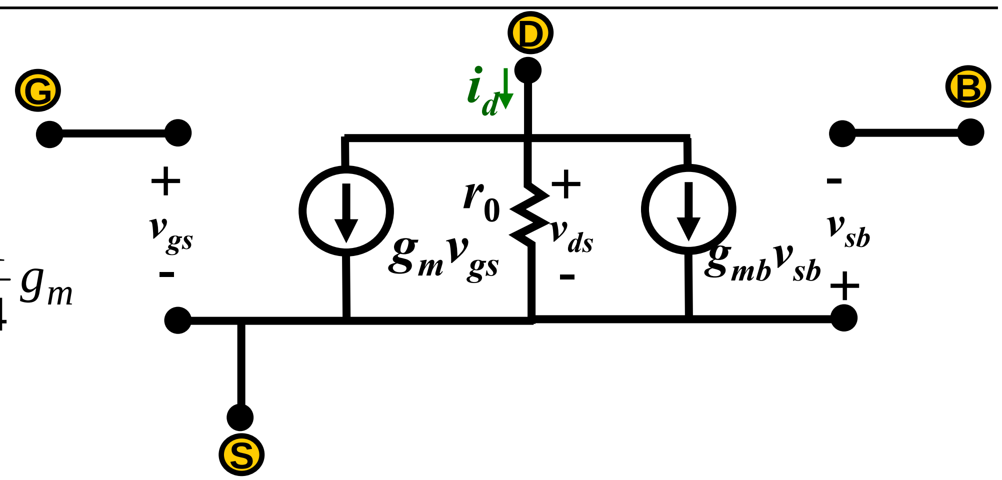
Summary of *MOSFET* models

Model	Circuit Symbol	Equations	Circuit	Comments
Large signal model of the n-channel MOSFET operating in the saturation region		**Under d.c. condition,** $V_{GS} > V_{TH}$ $V_{DS} \geq V_{GS} - V_{TH}$ $I_{Dsat} = K_n\,(V_{GS} - V_{TH})^2$		
Large signal model of the n-channel MOSFET operating in the linear region		**Under d.c. condition,** $V_{GS} > V_{TH}$ $V_{DS} < V_{GS} - V_{TH}$ **For small V_D,** $I_D \approx 2K_n(V_{GS} - V_{TH})V_{DS}$		$R_{DS} =$ $1/[2K_n(V_{GS} - V_{TH})]$

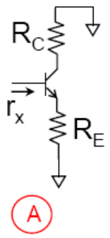
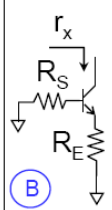
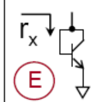
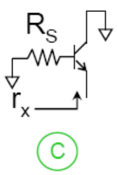
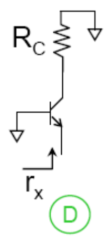
Summary of *MOSFET* models

Model	Circuit Symbol	Equations	Circuit	Comments
Large signal model of the p-channel MOSFET operating in the saturation region		**Under d.c. condition,** $\|V_{GS}\| > \|V_{TH}\|$ $\|V_{DS}\| \geq \|V_{GS}\| - \|V_{TH}\|$ $\|I_{Dsat}\| = K_p\,(\|V_{GS}\| - \|V_{TH}\|)^2$ V_{GS}, V_{TH} **are negative**		
Large signal model of the p-channel MOSFET operating in the linear region		**Under d.c. condition,** $\|V_{GS}\| > \|V_{TH}\|$ $\|V_{DS}\| < \|V_{GS}\| - \|V_{TH}\|$ **For small** V_D, $\|I_D\| \approx 2K_p(\|V_{GS}\| - \|V_{TH}\|)\|V_{DS}\|$		

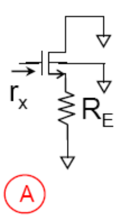
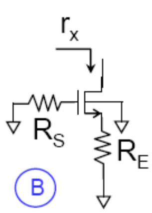
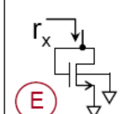
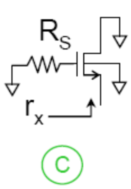
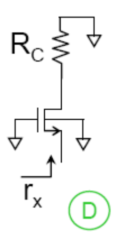
Summary of *MOSFET* models

Model	Circuit Symbol	Equations	Circuit	Comments
Small signal model of the MOSFET (both n-channel and p-channel)		$g_m = 2\sqrt{K\|I_D\|}$ $r_0 = \frac{1}{\lambda I_D}$		**I_D is the drain current at the d.c. bias point, K is the transconductance factor, λ is the channel length modulation factor.**
Small signal model of the MOSFET, including body effect (body not tied to source)		$g_{mb} \approx -\frac{1}{4} g_m$		

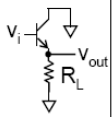
BJT Equivalent Resistance Summary (Table 1)

Conf	r_x	Conf	r_x	Conf	r_x
	$r_\pi + (1+\beta)R_E$ $\approx r_\pi(1+g_m R_E)$		$r_o\left\{1+g_m\left[(r_\pi+R_S)//R_E\right]\left(\frac{r_\pi}{r_\pi+R_S}\right)\right\}$ *If* $R_S=0$ *and* $r_\pi << R_E$ $\Rightarrow r_{x,\max}=r_o(\beta+1)$		$\frac{1}{g_m}$
	$\frac{R_S+r_\pi}{1+\beta}//r_o$ $\approx \frac{R_S}{1+\beta}+\frac{1}{g_m}$		$\frac{1}{g_m}\times\frac{r_o+R_C}{r_o+R_C/\beta}$		

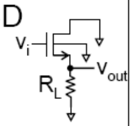
MOS Equivalent Resistance Summary (Table 2)

Conf	r_x	Conf	r_x	Conf	r_x
	∞		$r_o\left[1+(g_m-g_{mb})R_E\right]$		$\frac{1}{g_m}$
	$\frac{1}{g_m-g_{mb}}$		$\frac{1}{g_m-g_{mb}}\times\frac{r_o+R_C}{r_o}$		

BJT Amplifier Configurations (Table 3)

BJT	G_m	A_V
CE (A)	g_m	Derive Based on 2-ports Network
CB (B)	$-g_m$	Derive Based on 2-ports Network
CC (C) 	Too Complex To Be Useful	$\frac{g_m R_L}{1+g_m R_L}$
CE with Emitter Degeneration (D)	$\frac{g_m}{1+g_m R_E}$	Derive Based on 2-ports Network

MOS Amplifier Configurations (Table 4)

MOS	G_m	A_V
CS (A)	g_m	Derive Based on 2-ports Network
CG (B)	$-(g_m - g_{mb})$ $Drop\ \ g_{mb}\ \ if\ \ no\ \ body\ \ effect$	Derive Based on 2-ports Network
CD (C) 	Too Complex To Be Useful	$\frac{g_m R_L}{1+(g_m - g_{mb})R_L} \approx \frac{g_m}{g_m - g_{mb}}$ $Drop\ \ g_{mb}\ \ if\ \ no\ \ body\ \ effect$
CS with R_E (D)	$\frac{g_m}{1+(g_m - g_{mb})R_E}$ $Drop\ \ g_{mb}\ \ if\ \ no\ \ body\ \ effect$	Derive Based on 2-ports Network

1) Logic Gates:

For K transistors in series:

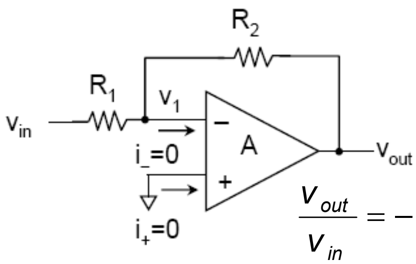
$$\left(\frac{W}{L}\right)_{eq} = \left[\left(\frac{W}{L}\right)_1^{-1} + \left(\frac{W}{L}\right)_2^{-1} + \cdots + \left(\frac{W}{L}\right)_K^{-1}\right]^{-1}$$

For K transistors in parallel:

$$\left(\frac{W}{L}\right)_{eq} = \left(\frac{W}{L}\right)_1 + \left(\frac{W}{L}\right)_2 + \cdots + \left(\frac{W}{L}\right)_K$$

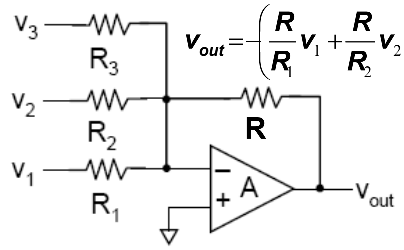
2) Opamp Circuits:

Inverting Amplifier



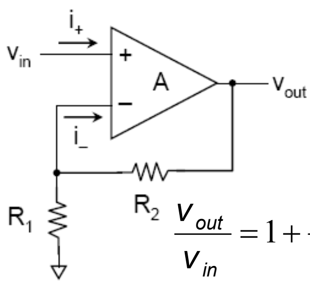
$$\frac{v_{out}}{v_{in}} = -\frac{R_2}{R_1}$$

Summing Amplifier



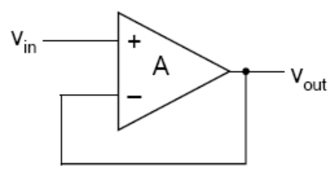
$$v_{out} = -\left(\frac{R}{R_1}v_1 + \frac{R}{R_2}v_2 + \frac{R}{R_3}v_3\right)$$

Non-inverting Amplifier



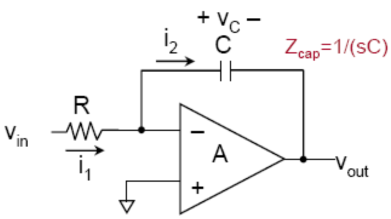
$$\frac{v_{out}}{v_{in}} = 1 + \frac{R_2}{R_1}$$

Buffer



$$\frac{v_{out}}{v_{in}} = 1$$

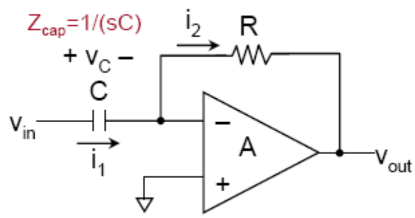
Integrator



$$\frac{v_{out}}{v_{in}} = -\frac{1}{sCR}$$

$$v_{out}(t) = -\frac{1}{RC}\int v_{in}(t)dt$$

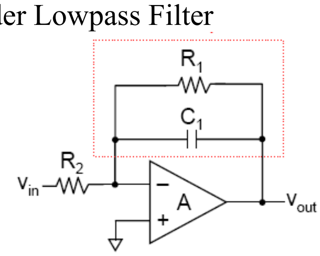
Differentiator



$$\frac{v_{out}}{v_{in}} = -sCR$$

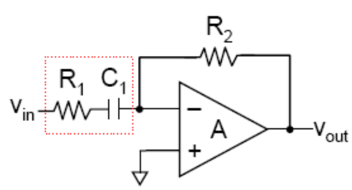
$$v_{out}(t) = -CR\frac{dv_{in}(t)}{dt}$$

First Order Lowpass Filter



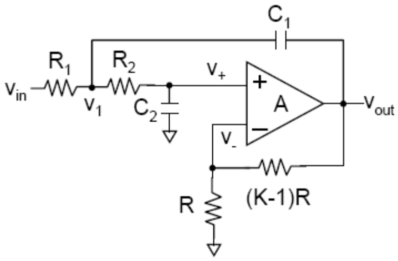
$$\frac{v_{out}}{v_{in}} = -\frac{R_1}{R_2} \times \frac{1}{sC_1R_1 + 1}$$

First Order Highpass Filter



$$\frac{v_{out}}{v_{in}} = -\frac{R_2}{R_1} \times \frac{s}{s + \frac{1}{C_1R_1}}$$

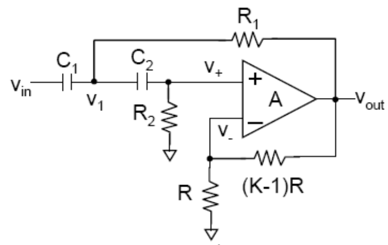
SK Lowpass Filter



$$\frac{v_{out}}{v_{in}} = \frac{\dfrac{K}{C_1C_2R_1R_2}}{s^2 + s\left(\dfrac{1}{C_1R_1}+\dfrac{1}{C_2R_2}+\dfrac{1}{C_1R_2}-\dfrac{K}{C_2R_2}\right)+\dfrac{1}{C_1C_2R_1R_2}}$$

$$= \frac{H_o\omega_o^2}{s^2+\dfrac{\omega_o}{Q}s+\omega_o^2}$$

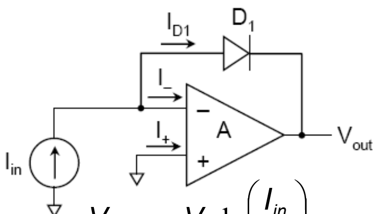
SK Highpass Filter



$$\frac{v_{out}}{v_{in}} = \frac{Ks^2}{s^2 + s\left(\dfrac{1}{C_2R_2}+\dfrac{1}{C_1R_2}+\dfrac{1}{C_1R_1}-\dfrac{K}{C_1R_1}\right)+\dfrac{1}{C_1C_2R_1R_2}}$$

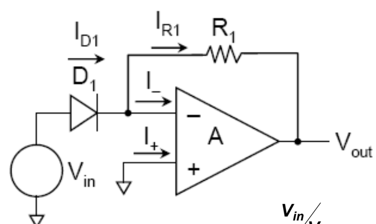
$$= \frac{H_os^2}{s^2+\dfrac{\omega_o}{Q}s+\omega_o^2}$$

Logarithm Amplifier



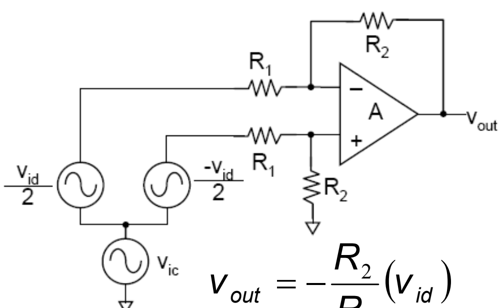
$$V_{out} = -V_T \ln\left(\frac{I_{in}}{I_S}\right)$$

Exponential Amplifier



$$V_{out} = -R_1 I_S e^{V_{in}/V_T}$$

Instrumentation Amplifier



$$v_{out} = -\frac{R_2}{R_1}(v_{id})$$

Super Diode