

EE Formula Sheet

§1.1 - Semiconductor Materials

DC variables are denoted by uppercase letters and uppercase subscripts.

Semiconductor constants		
Material	$E_g(\text{eV})$	$B(\text{cm}^{-3}\text{K}^{-3/2})$
Silicon (Si)	1.1	5.23×10^{-15}
Gallium arsenide (GaAs)	1.4	2.10×10^{-14}
Germanium (Ge)	0.66	1.66×10^{-15}

Intrinsic carrier concentration of Si

$$n_i = BT^{3/2}e^{-\frac{E_g}{2kT}}$$

Where:

- k is Boltzmann's constant $86 \times 10^{-6} \text{ eV/K}$
- B is a coefficient related to the specific semiconductor material
- E_g is the bandgap energy (eV)
- T is the temperature (K)
- e , in this context, represents the exponential function

Extrinsic (doped) semiconductors

$n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$, intrinsic carrier concentration @ 300K for Si

$n_o = \frac{n^2_i}{N_a}$, Electron concentration

$p_o = \frac{n^2_i}{N_d}$, Hole concentration

Majority carrier: N-type: electrons, P-type: holes

Drift and Diffusion Currents

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§1.2 - The PN Junction

$V_{bi} = V_T \ln\left(\frac{N_a N_d}{n^2_i}\right)$, Built In barrier (V_f)

$C_j = C_{j0} \left(1 + \frac{V_R}{V_{bi}}\right)$, Junction Capacitance

$i_D = I_S \left(e^{\left(\frac{v_D}{nV_T}\right)} - 1\right)$, Diode Current, where $V_T = 26\text{mV}$ @ 300K

§1.3 - Diode Circuits: DC Analysis and Models

- Use KVL when $V_D \geq V_y$. Use open circuit when $V_D < V_y$
- Use PWL to plot the diode voltage where slope of diode cut in voltage is $m = 1/R_f$
- Use KVL formula of the circuit to plot the load line. (Arrange formula in slope-intercept form.)
- The Q -point is at the intersection of the PWL and load line plots.

§1.4 - Diode Circuits: AC Analysis and Models

First, analyze the DC portion, then the AC portion.

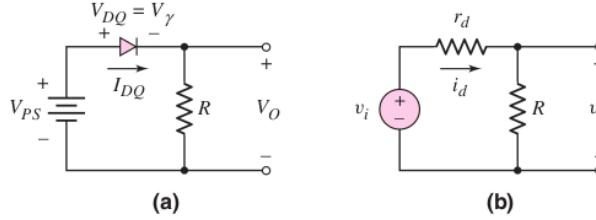


Figure 1.36 Equivalent circuits: (a) dc and (b) ac

$R_d = \frac{1}{g_d} = \frac{V_T}{I_{DQ}}$, Small Signal Diffusion Resistance

$i_d = \left(\frac{I_{DQ}}{V_T}\right) \cdot v_d = g_d \cdot v_d$, AC diode current

$v_d = \left(\frac{V_T}{I_{DQ}}\right) \cdot i_d = r_d \cdot i_d$, AC diode voltage

where g_d and r_d respectively, are the diode small-signal incremental conductance and resistance, also called the diffusion conductance and diffusion resistance.

$C_d = \left(\frac{dQ}{dV_D}\right)$, Diffusion Capacitance

Small-Signal Equivalent Circuit

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§2.1 - Rectifier Circuits

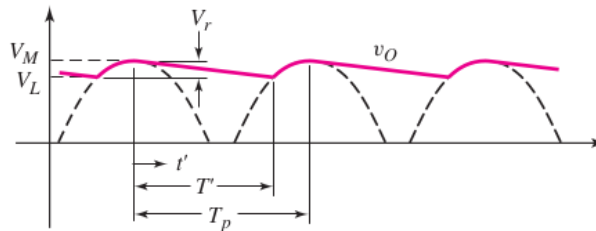
$\frac{v_s}{v_s} = \frac{N_1}{N_2}$, Transformer voltage to turn-ratio relationship.

Center tapped formulae

$v_s(\text{max}) = v_o(\text{max}) + V_y$, Peak

$v_r(\text{max}) = 2v_s(\text{max}) - V_y$, Peak Inverse Voltage

Bridge rectifier formulae



$v_s(\text{max}) = v_o(\text{max})$, Peak

$v_r(\text{max}) = v_s(\text{max}) - V_y$, Peak Inverse Voltage

$v_o(t) = V_M e^{t'/RC}$, Average Vout

$v_L = V_M e^{T'/RC}$, Minimum Vout

$v_r = V_M - V_L = \frac{V_M}{2fRC}$, Ripple on Vout

§2.4 - Clippers and Clampers

Clippers clip signals, and clampers shift the entire waveform.

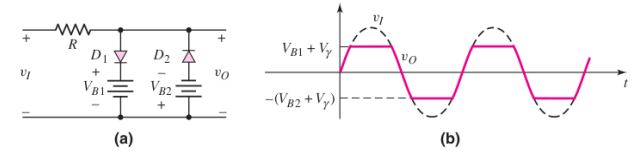


Figure 2.22 A parallel-based diode clipper circuit and its output response

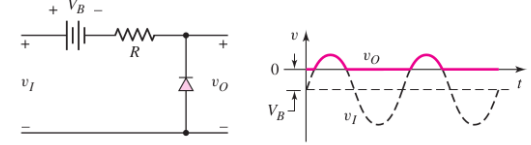


Figure 2.25 Series-based diode clipper circuit and resulting output response

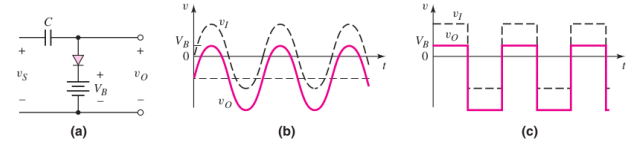


Figure 2.28 Action of a diode clamper circuit with a voltage source assuming an ideal diode ($V_r = 0$): (a) the circuit, (b) steady-state sinusoidal input and output signals, and (c) steady-state square-wave input and output signals

§3.1 - MOS Field-Effect Transistor

N-Channel

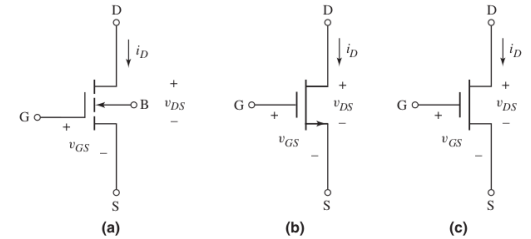


Figure 3.12 The n-channel enhancement-mode MOSFET: (a) conventional circuit symbol, (b) circuit symbol that will be used in this text, and (c) a simplified circuit symbol used in more advanced texts

$v_{DS}(\text{sat}) = v_{GS} - V_{TN}$, Saturation Voltage, where V_{TN} is the threshold voltage.

$i_D = K_n [2(v_{GS} - V_{TN})v_{DS} - v_{DS}^2]$, I-V Characteristic in non-saturation.

$i_D = K_n (v_{GS} - V_{TN})^2$, I-V Characteristic in saturation.

$C_{ox} = \epsilon_{ox}/t_{ox}$, Oxide capacitance per unit area.

$\epsilon_{ox} = (3.9)(8.85 \times 10^{-14} \text{ F/cm})$, Oxide permittivity for Si devices.

$K_n = \frac{W \mu_n C_{ox}}{2L}$, Conduction Parameter

$K_n = \frac{k'_n}{2} \cdot \frac{W}{L}$, Conduction Parameter

$k'_n = \mu_n C_{ox}$, Process conduction parameter.

μ_n , Electron mobility in the inversion layer.

P-Channel

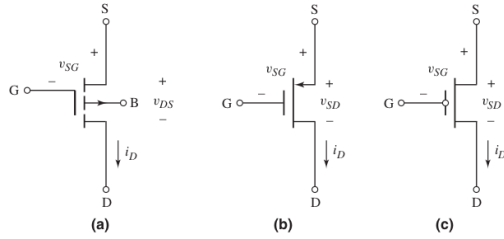


Figure 3.13 The p-channel enhancement-mode MOSFET: (a) conventional circuit symbol, (b) circuit symbol that will be used in this text, and (c) a simplified circuit symbol used in more advanced texts

$i_D = K_p [2(v_{SG} - V_{TP})v_{SD} - v_{SD}^2]$, I-V Characteristic in non-saturation.

$i_D = K_p (v_{SG} - V_{TP})^2$, I-V Characteristic in saturation.

$K_p = \frac{W \mu_p C_{ox}}{2L}$, Conduction Parameter

$K_p = \frac{k'_p}{2} \cdot \frac{W}{L}$, Conduction Parameter

$k'_p = \mu_p C_{ox}$

Table 3.1 Summary of the MOSFET current-voltage relationships

NMOS	PMOS
Nonsaturation region ($v_{DS} < v_{DS}(sat)$) $i_D = K_n [2(v_{GS} - V_{TN})v_{DS} - v_{DS}^2]$	Nonsaturation region ($v_{SD} < v_{SD}(sat)$) $i_D = K_p [2(v_{SG} + V_{TP})v_{SD} - v_{SD}^2]$
Saturation region ($v_{DS} > v_{DS}(sat)$) $i_D = K_n (v_{GS} - V_{TN})^2$	Saturation region ($v_{SD} > v_{SD}(sat)$) $i_D = K_p (v_{SG} + V_{TP})^2$
Transition point $v_{DS}(sat) = v_{GS} - V_{TN}$	Transition point $v_{SD}(sat) = v_{SG} + V_{TP}$
Enhancement mode $V_{TN} > 0$	Enhancement mode $V_{TP} < 0$
Depletion mode $V_{TN} < 0$	Depletion mode $V_{TP} > 0$

§3.2 - Mosfet DC Analysis

Establishes the DC operating point, Q . This is I_D and V_{DS}
A resistor on the source leg provides stability via negative feedback at the expense of reducing gain. Alternatively a CC bias may be used to increase stability without limiting gain.

Common Source Amplifiers

N-Type

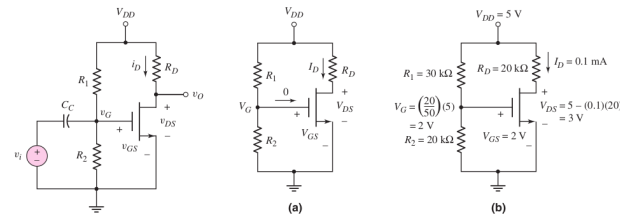


Figure 3.24 An NMOS common-source circuit

Figure 3.25 (a) The dc equivalent circuit of the NMOS common-source circuit and (b) the NMOS circuit for Example 3.3, showing current and voltage values

$$v_G = v_{GS} = \left(\frac{R_2}{R_1 + R_2} \right) V_{DD}$$

$$I_D = K_n (V_{GS} - V_{TN})^2$$

$$V_{DS} = V_{DD} - I_D R_D$$

$$P_T = I_D V_{DS}, \text{ Power}$$

If $V_{DS} > V_{DS}(sat)$, where $V_{DS}(sat) = V_{GS} - V_{TN}$, then the transistor is biased in the saturation region

P-Type

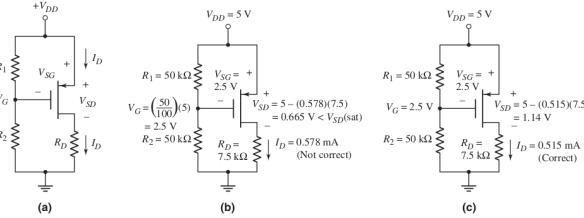


Figure 3.26 (a) A PMOS common-source circuit, (b) the PMOS common-source circuit for Example 3.4 showing current and voltage values when the saturation-region bias assumption is incorrect, and (c) the circuit for Example 3.4 showing current and voltage values when the nonsaturation-region bias assumption is correct

$$v_G = \left(\frac{R_2}{R_1 + R_2} \right) V_{DD}$$

$$v_{SG} = V_{DD} - V_G$$

$$I_D = K_p (V_{SG} + V_{TP})^2$$

$$V_{SD} = V_{DD} - I_D R_D$$

$$P_T = I_D V_{DS}, \text{ Power}$$

If $V_{SD} > V_{SD}(sat)$, where $V_{SD}(sat) = V_{SG} + V_{TP}$, then the transistor is biased in the saturation region

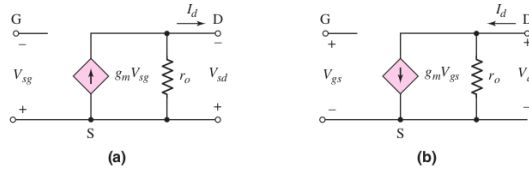


Figure 4.11 Small signal equivalent circuit of a p-channel MOSFET showing (a) the conventional voltage polarities and current directions and (b) the case when the voltage polarities and current directions are reversed.

§4.1 - Mosfet amplifier

$$g_m = 2\sqrt{K_n I_{DQ}}, \text{ Trans-conductance}$$

$$r_o = \frac{1}{\lambda I_D}$$

$$r_{eq} = \frac{1}{g_m}, \text{ Small Sig curr source equivalent resistance.}$$

§6 - BJT Amplifier

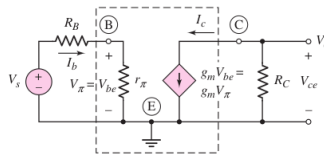


Figure 6.11 The small-signal equivalent circuit of the common-emitter circuit shown in Figure 6.3. The small-signal hybrid- π model of the npn bipolar transistor is shown within the dotted lines.

$$g_m = 2\sqrt{K_n I_{DQ}},$$

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

$$g_m = 2K_n (V_{GS} - V_{TH}),$$

$$g_m = \frac{I_C}{V_{TH}},$$

$$r_o = \frac{1}{\lambda I_{DQ}},$$

$$r_o = \frac{V_A}{I_C},$$

$$r_\pi = \frac{V_T}{I_B},$$

$$r_\pi = \frac{\beta}{g_m},$$

$$A_v = -g_m \cdot R_C || R_L, \text{ Voltage Gain Formula}$$

Transistor DC Equivalent

$$V_{th} = \frac{V_{CC}}{R_1 + R_2} \cdot R_2,$$

$$R_{th} = R_1 || R_2,$$

$$V_{ce}(sat) \approx 0.2(typ),$$

$$I_E \approx I_C, \text{ In active region}$$

$$-\frac{1}{R_E - R_C}, \text{ load line slope, where } R_C \text{ \& } R_E \text{ are from the AC or DC equivalent circuit. A load line plot is } I_C \text{ vs } V_{CE}$$

$$I_{RE} = I_B(\beta + 1)R_E,$$

Terminology

Common Source: Input connected to gate, output connected to drain.

Common Drain (Source Follower): Input connected to gate, output connected to source.

Common Gate: Input connected to source, output connected to drain.

Transistor formulas

$$I_C = \beta \cdot I_B, \text{ Conduction Parameter}$$

$$I_B = \frac{I_E}{\beta + 1},$$

$$\alpha = \frac{I_C}{I_E}, \text{ Current Ratio}$$

$$I_C = I_E - I_B, \text{ Kirchhoff's Current Law}$$

$$V_{CE} = V_{BE} + V_{CB}, \text{ Voltage Relationships}$$

$$I_C \approx I_{C0} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right), \text{ BJT Current Equation}$$

$$I = I_0 \cdot \left(e^{\frac{V}{n \cdot V_T}} - 1 \right), \text{ Schottky Diode Equation}$$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2, \text{ MOSFET Drain Current Equation}$$

$$I_D = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_{TH})V_{DS} - \frac{V_{DS}^2}{2} \right], \text{ MOSFET Drain Current Equation (Triode Region)}$$

$$g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D}, \text{ Transconductance Parameter}$$

$$A_v = -g_m \cdot R_D, \text{ Voltage Gain Formula}$$

EE General Formulae

$$r_{ms} = \frac{1}{\sqrt{2}},$$

$$V = I \cdot R, \text{ Ohm's law.}$$

$$P = V \cdot I, \text{ DC Power.}$$

$$P = V \cdot I \cdot \cos(\theta), \text{ AC power.}$$

$$E = P \cdot t, \text{ Energy.}$$

$$C = \frac{Q}{V}, \text{ Capacitance.}$$

$$V = L \cdot \frac{di}{dt}, \text{ Inductance.}$$

$$\tau = R \cdot C, \text{ Time constant to reach 63.2\% of capacitors final voltage.}$$

$$\tau = \frac{L}{R}, \text{ Time constant to reach 63.2\% of inductors final value.}$$

$$\frac{N_1}{N_2} = \frac{V_1}{V_2}, \text{ Transformer turns ratio.}$$

$V_{\text{peak}} = \sqrt{2} \cdot V_{\text{rms}}$, Peak AC Voltage.

$V_{\text{rms}} = \frac{V_{\text{peak}}}{\sqrt{2}}$, RMS AC Voltage.

$V_{\text{avg}} = \frac{1}{T} \int_0^T V(t) dt$, RMS AC Voltage.

$V_{\text{out}} = V_{\text{in}} \cdot \frac{R_2}{R_1 + R_2}$, voltage divider.

$R_{\text{eq}} = R_1 + R_2 + \dots + R_n$, series resistors.

$\frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}$, Parallel resistors.

$\frac{1}{C_{\text{eq}}} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_n}$, Series capacitors.

$C_{\text{eq}} = C_1 + C_2 + \dots + C_n$, parallel capacitors.

Convert Polar to Rectangular

$$x = r \cos \theta$$

$$y = r \sin \theta$$

Exact Slope of a Tangent Line

$$\frac{dy}{dx} = \frac{dy/dt}{dx/dt}$$

Basic integration Rules

$$\int k f(u) du = k \int f(u) du + C,$$

$$\int [f(u) \pm g(u)] du = \int f(u) du \pm \int g(u) du, \int du = u + C,$$

$$\int u^n du = \frac{u^{n+1}}{n+1} + C, n \neq -1, \int \frac{du}{u} = \ln |u| + C,$$

$$\int \frac{u}{du} = \frac{u^2}{2} + C, \int e^u du = e^u + C, \int e^{4u} = \frac{e^{4u}}{4} + C,$$

$$\int a^u du = \left(\frac{1}{\ln a} \right) a^u + C,$$

Some Integrals

$$\int \sin u du = -\cos u + C, \int \cos u du = \sin u + C,$$

$$\int \tan u du = -\ln |\cos u| + C, \int \cot u du = \ln |\sin u| + C,$$

$$\int \sec u du = \ln |\sec u + \tan u| + C,$$

$$\int \csc u du = -\ln |\csc u + \cot u| + C, \int \sec^2 u du = \tan u + C,$$

$$\int \csc^2 u du = -\cot u + C, \int \sec u \tan u du = \sec u + C,$$

$$\int \csc u \cot u du = -\csc u + C, \int \frac{du}{\sqrt{a^2 - u^2}} = \arcsin \frac{u}{a} + C,$$

$$\int \frac{du}{a^2 + u^2} = \frac{1}{a} \arctan \frac{u}{a} + C, \int \frac{du}{u \sqrt{u^2 - a^2}} = \frac{1}{a} \operatorname{arcsec} \frac{|u|}{a} + C,$$

$$\int \sin 3x = -\frac{1}{3} \cos 3x, \int e^{-4x} = \frac{e^{-4x}}{-4}$$

$$\int k dx = kx + C, \int x dx = \frac{1}{2} x^2 + C, \int x^2 dx = \frac{1}{3} x^3 + C,$$

$$\int \frac{1}{x} dx = \ln |x| + C, \int e^x dx = e^x + C, \int k^u du = \frac{k^u}{\ln k} + C,$$

$$\int \ln x dx = x \ln x - x + C, \int \cos x dx = \sin x + C,$$

$$\int \sin x dx = -\cos x + C, \int \sec^2 x dx = \tan x + C,$$

$$\int x^n dx = \frac{x^{n+1}}{n+1} + C, \int \tan x = -\ln(\cos x) + C,$$

Integration by Parts

$$\int u dv = uv - \int v du$$

Some Identities

$$\sin 2x = 2 \sin x \cos x$$

Pythagorean:

$$\sin^2 x + \cos^2 x = 1, 1 + \tan^2 x = \sec^2 x, 1 + \cot^2 x = \csc^2 x$$

Reciprocal:

$$\sin x = \frac{1}{\csc x}, \cos x = \frac{1}{\sec x}, \tan x = \frac{\sin x}{\cos x} = \frac{1}{\cot x}$$

$$\csc x = \frac{1}{\sin x}, \sec x = \frac{1}{\cos x}, \cot x = \frac{\cos x}{\sin x} = \frac{1}{\tan x}$$

Half Angle:

$$\sin^2 x = \frac{1}{2}(1 - \cos 2x), \cos^2 x = \frac{1}{2}(1 + \cos 2x)$$

Additional Notes:

$$\ln(x * y) = \ln(x) + \ln(y), \ln(x/y) = \ln(x) - \ln(y)$$

$$\ln x^a = a \ln x, \tan \theta = \frac{\sin \theta}{\cos \theta}$$

$$ax^2 + bx + c = 0, x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$\ln a = c \Leftrightarrow e^c = a$$

$$\sqrt[n]{a} = a^{\frac{1}{n}}, a^{-n} = \frac{1}{a^n}, \sqrt[n]{a^m} = a^{\frac{m}{n}}, a^0 = 1, (a^m)^n = a^{mn},$$

$$a^m * a^n = a^{m+n}, \frac{a^m}{a^n} = a^{m-n}, \text{ Rewrite } \sqrt{5x} \text{ as } \sqrt{5}\sqrt{x},$$

Some Derivatives:

$$\frac{d}{du} \sin u = (\cos u)u', \frac{d}{du} \cos u = -(\sin u)u',$$

$$\frac{d}{du} \tan u = (\sec^2 u)u', \frac{d}{du} \cot u = -(\csc^2 u)u',$$

$$\frac{d}{du} \sec u = (\sec u \tan u)u', \frac{d}{du} \csc u = -(\csc u \cot u)u',$$

$$\frac{d}{du} \arcsin u = \frac{u'}{\sqrt{1-u^2}}, \frac{d}{du} \arccos u = \frac{-u'}{\sqrt{1-u^2}},$$

$$\frac{d}{du} \arctan u = \frac{u'}{1+u^2}, \frac{d}{du} \operatorname{arccot} u = \frac{-u'}{1+u^2},$$

$$\frac{d}{du} \operatorname{arcsec} u = \frac{u'}{|u|\sqrt{u^2-1}}, \frac{d}{du} \operatorname{arccsc} u = \frac{-u'}{|u|\sqrt{u^2-1}}$$

$$\frac{d}{du} [\ln u] = \frac{1}{u} u', \frac{d}{dx} [e^{-x}] = -e^{-x}, e^{\ln a} = a$$

$$\frac{d}{du} [\sqrt{u}] = \frac{u'}{2\sqrt{u}}, e^{3x} = 3e^{3x}, \frac{d}{dx} [x] = 1, \frac{d}{dx} [c] = 0,$$

$$\frac{d}{du} \left[\frac{1}{u} \right] = \frac{1}{u^2}, \frac{du}{u} = \ln |u|,$$

