EE Formula Sheet

§1.1 - Semiconductor Materials

DC variables are denoted by uppercase letters and uppercase subscripts.

Semiconductor constants		
Material	$Eg(eV)$	$B(cm^{-3}K^{-3/2})$
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

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

Where:

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

Extrinsic (doped) semiconductors

$n_i = 1.5 \times 10^{10}$ 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)
$C_j = C_{jo}\left(1 + \frac{V_R}{V_{bi}}\right)$, Junction Capacitance
$i_D = I_S\left(e^{\left(\frac{v_D}{nV_T}\right)} - 1\right)$, Diode Current, where $V_T = 26mV$ @ 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.

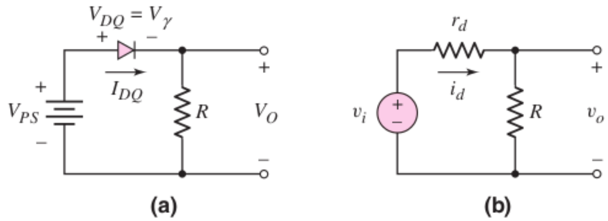

Figure 1.36 Equivalent circuits: (a) dc and (b) ac

$R_d = \frac{1}{g_d} = \frac{V_T}{I_{DQ}}$, 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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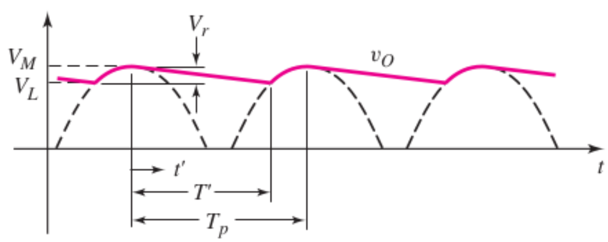
§2.1 - Rectifier Circuits

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

Center tapped formulae

$v_s(max)) = v_o(max) + V_y$, Peak
$v_r(max) = 2v_S(max) - V_y$, Peak Inverse Voltage

Bridge rectifier formulae



$v_S(max) = v_O(max)$, Peak
$v_R(max) = v_S(max) - V_y$, 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.

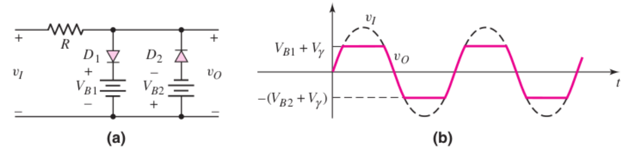


Figure 2.22 A parallel-based diode clipper circuit and its output response

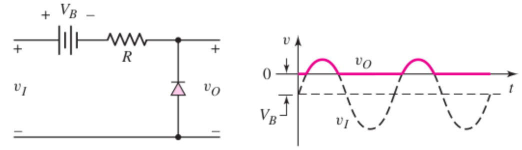


Figure 2.25 Series-based diode clipper circuit and resulting output response

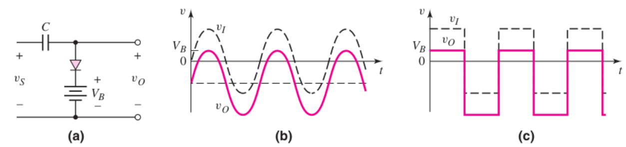


Figure 2.28 Action of a diode clamper circuit with a voltage source assuming an ideal diode ($V_\gamma = 0$): (a) the circuit, (b) steady-state sinusoidal input and output signals, and (c) steady-state square-wave input and output signals

§3.1 - MOS Field-Effect Transistor

N-Channel

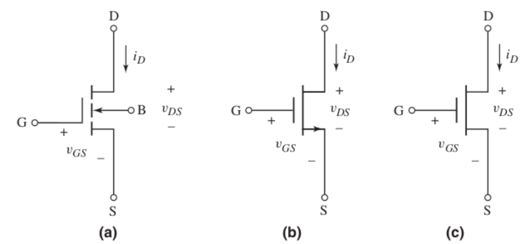


Figure 3.12 The n-channel enhancement-mode MOSFET: (a) conventional circuit symbol, (b) circuit symbol that will be used in this text, and (c) a simplified circuit symbol used in more advanced texts

$v_{DS}(sat) = v_{GS} - V_{TN}$, Saturation Voltage, where V_{TN} is the threshold voltage.
$i_D = K_n\left[2(v_{GS} - V_{TN})v_{DS} - v_{DS}^2\right]$, 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.
$\epsilon_{ox} = (3.9)(8.85 \times 10^{-14}$ 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

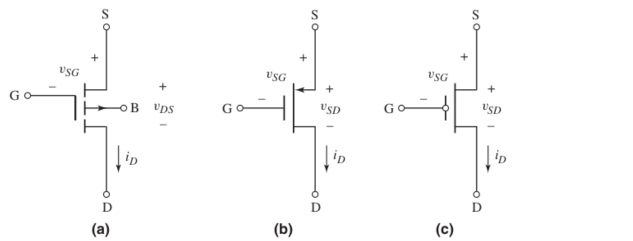


Figure 3.13 The p-channel enhancement-mode MOSFET: (a) conventional circuit symbol, (b) circuit symbol that will be used in this text, and (c) a simplified circuit symbol used in more advanced texts

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

§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

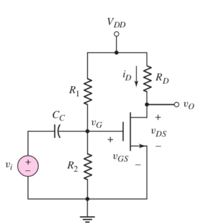


Figure 3.24 An NMOS common-source circuit

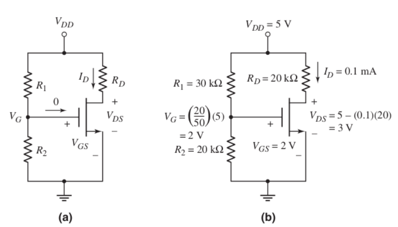


Figure 3.25 (a) The dc equivalent circuit of the NMOS common-source circuit and (b) the NMOS circuit for Example 3.3, showing current and voltage values

$v_G = v_{GS} = \left(\frac{R2}{R1+R2}\right)V_{DD}$
$I_D = K_n(V_{GS} - V_{TN})^2$
$V_{DS} = V_{DD} - I_D R_D$
$P_T = I_D V_{DS}$, 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

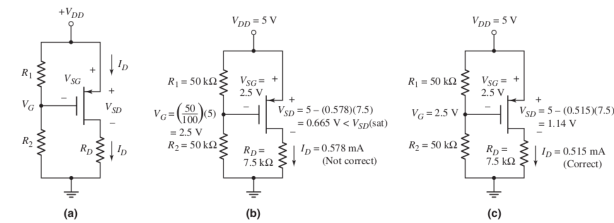


Figure 3.26 (a) A PMOS common-source circuit, (b) the PMOS common-source circuit for Example 3.4 showing current and voltage values when the saturation-region bias assumption is incorrect, and (c) the circuit for Example 3.4 showing current and voltage values when the nonsaturation-region bias assumption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

$v_G = \left(\frac{R2}{R1+R2}\right)V_{DD}$
$v_{SG} = V_{DD} - V_G$
$I_D = K_p(V_{SG} + V_{TP})^2$
$V_{SD} = V_{DD} - I_D R_D$
$P_T = I_D V_{DS}$, Power
If $V_{SD} > V_{SD}(sat)$, where $V_{SD}(sat) = V_{SG} + V_{TP}$, then the transistor is biased in the saturation region

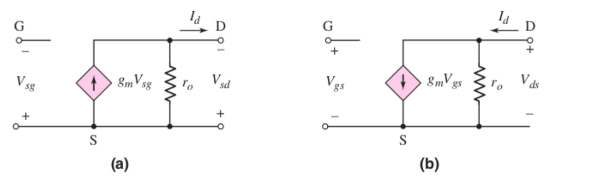


Figure 4.11 Small signal equivalent circuit of a p-channel MOSFET showing (a) the conventional voltage polarities and current directions and (b) the case when the voltage polarities and current directions are reversed.

§4.1 - Mosfet amplifier

$g_m = 2\sqrt{K_n I_{DQ}}$, Trans-conductance
$r_o = \frac{1}{\lambda I_D}$
$r_{eq} = \frac{1}{g_m}$, Small Sig curr source equivalent resistance.

§6 - BJT Amplifier

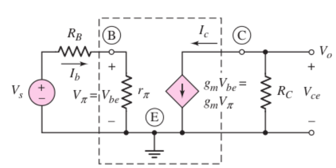


Figure 6.11 The small-signal equivalent circuit of the common-emitter circuit shown in Figure 6.3. The small-signal hybrid-π model of the npn bipolar transistor is shown within the dotted lines.

$g_m = 2\sqrt{K_n I_{DQ}}$,
$g_m = \frac{I_D}{V_{GS}}$,
$g_m = 2K_n(V_{GS} - V_{TH})$,
$g_m = \frac{I_C}{V_T H}$,
$r_o = \frac{1}{\lambda I_{DQ}}$,
$r_o = \frac{V_A}{I_C}$,
$r_\pi = \frac{V_T}{I_B}$,
$r_\pi = \frac{\beta}{g_m}$,
$A_v = -g_m \cdot R_C || R_L$, Voltage Gain Formula

Transistor DC Equivalent

$V_{th} = \frac{V_{cc}}{R_1 + R_2} \cdot R_2$,
$R_{th} = R_1 || R_2$,
$V_{ce}(sat) \approx 0.2(typ)$,
$I_E \approx I_C$, In active region
$-\frac{1}{R_E - R_C}$, load line slope, where R_C & R_E are from the AC or DC equivalent circuit. A load line plot is I_C 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

$I_C = \beta \cdot I_B$, Conduction Parameter
$I_B = \frac{I_E}{\beta + 1}$,
$\alpha = \frac{I_C}{I_E}$, Current Ratio
$I_C = I_E - I_B$, Kirchhoff's Current Law
$V_{CE} = V_{BE} + V_{CB}$, Voltage Relationships
$I_C = I_{C0}\left(e^{\frac{V_{BE}}{V_T}} - 1\right)$, BJT Current Equation
$I = I_0 \cdot \left(e^{\frac{V}{n \cdot V_T}} - 1\right)$, Schottky Diode Equation
$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2$, MOSFET Drain Current Equation
$I_D = \mu_n C_{ox}\frac{W}{L}\left[(V_{GS} - V_{TH})V_{DS} - \frac{V_{DS}^2}{2}\right]$, MOSFET Drain Current Equation (Triode Region)
$g_m = \sqrt{2\mu_n C_{ox}\frac{W}{L} I_D}$, Transconductance Parameter
$A_v = -g_m \cdot R_D$, Voltage Gain Formula

EE General Formulae

$rms = \frac{1}{\sqrt{2}}$,
$V = I \cdot R$, Ohm's law.
$P = V \cdot I$, DC Power.
$P = V \cdot I \cdot \cos(\theta)$, AC power.
$E = P \cdot t$, Energy.
$C = \frac{Q}{V}$, Capacitance.
$V = L \cdot \frac{di}{dt}$, Inductance.
$\tau = R \cdot C$, Time constant to reach 63.2% of capacitors final voltage.
$\tau = \frac{L}{R}$, Time constant to reach 63.2% of inductors final value.
$\frac{N_1}{N_2} = \frac{V_1}{V_2}$, 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.
$R_{\text{eq}} = R_1 + R_2 + \ldots + R_n$, series resistors.
$\frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$, Parallel resistors.
$\frac{1}{C_{\text{eq}}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_n}$, Series capacitors.
$C_{\text{eq}} = C_1 + C_2 + \ldots + C_n$, 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

$\int kf(u)du = k\int f(u)du + C$,
$\int [f(u) \pm g(u)]du = \int f(u)du \pm \int g(u)du$, $\int du = u + C$,
$\int u^n du = \frac{u^{n+1}}{n+1} + C, n \neq -1$, $\int \frac{du}{u} = \ln|u| + C$,
$\int \frac{u}{du} = \frac{u^2}{2} + C$, $\int e^u du = e^u + C$,$\int e^{4u} = \frac{e^{4u}}{4} + C$,
$\int a^u du = \left(\frac{1}{\ln a}\right) a^u + C$,

Some Integrals

$\int \sin u du = -\cos u + C$, $\int \cos u du = \sin u + C$,
$\int \tan u du = -\ln|\cos u| + C$, $\int \cot u du = \ln|\sin u| + C$,
$\int \sec u du = \ln|\sec u + \tan u| + C$,
$\int \csc u du = -\ln|\csc u + \cot u| + C$, $\int \sec^2 u du = \tan u + C$,
$\int \csc^2 u du = -\cot u + C$, $\int \sec u \tan u du = \sec u + C$,
$\int \csc u \cot u du = -\csc u + C$, $\int \frac{du}{\sqrt{a^2-u^2}} = \arcsin\frac{u}{a} + C$,
$\int \frac{du}{a^2+u^2} = \frac{1}{a}\arctan\frac{u}{a} + C$, $\int \frac{du}{u\sqrt{u^2-a^2}} = \frac{1}{a}\text{arcsec}\frac{|u|}{a} + C$,
$\int \sin 3x = -\frac{1}{3}\cos 3x$, $\int e^{-4x} = \frac{e^{-4x}}{-4}$

$\int kdx = kx + C$, $\int xdx = \frac{1}{2}x^2 + C$, $\int x^2 dx = \frac{1}{3}x^3 + C$,
$\int \frac{1}{x}dx = \ln|x| + C$, $\int e^x dx = e^x + C$,$\int k^u du = \frac{k^u}{\ln u} + C$,
$\int \ln x dx = x\ln x - x + C$, $\int \cos x dx = \sin x + C$,
$\int \sin x dx = -\cos x + C$, $\int \sec^2 x dx = \tan x + C$,
$\int x^n dx = \frac{x^{n+1}}{n+1} + C$, $\int \tan x = -\ln(\cos x) + C$,

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:

$\ln(x * y) = \ln(x) + \ln(y)$, $\ln(x/y) = \ln(x) - \ln(y)$
$\ln x^a = a\ln x$, $\tan\theta = \frac{\sin\theta}{\cos\theta}$
$ax^2 + bx + c = 0$, $x = \frac{-b\pm\sqrt{b^2-4ac}}{2a}$
$\ln a = c \equiv e^c = a$
$\sqrt[n]{a} = a^{\frac{1}{n}}$, $a^{-n} = \frac{1}{a^n}$, $\sqrt[n]{a^m} = a^{\frac{m}{n}}$, $a^0 = 1$, $(a^m)^n = a^{mn}$,
$a^m * a^n = a^{m+n}$, $\frac{a^m}{a^n} = a^{m-n}$, Rewrite $\sqrt{5x}$ as $\sqrt{5}\sqrt{x}$,

Some Derivatives:

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

$\frac{d}{du}\arcsin u = \frac{u'}{\sqrt{1-u^2}}$, $\frac{d}{du}\arccos u = \frac{-u'}{\sqrt{1-u^2}}$,
$\frac{d}{du}\arctan u = \frac{u'}{1+u^2}$, $\frac{d}{du}\text{arccot } u = \frac{-u'}{1+u^2}$,
$\frac{d}{du}\text{arcsec } u = \frac{u'}{|u|\sqrt{u^2-1}}$, $\frac{d}{du}\text{arccsc } u = \frac{-u'}{|u|\sqrt{u^2-1}}$
$\frac{d}{du}[\ln u] = \frac{1}{u}u'$, $\frac{d}{dx}[e^{-x}] = -e^{-x}$, $e^{\ln a} = a$
$\frac{d}{du}[\sqrt{u}] = \frac{u'}{2\sqrt{u}}$, $e^{3x} = 3e^{3x}$, $\frac{d}{dx}[x] = 1$, $\frac{d}{dx}[c] = 0$,
$\frac{d}{du}[\frac{1}{u}] = \frac{1}{u^2}$, $\frac{du}{u} = \ln|u|$,