EE Formula Sheet

Constants

$$q = 1.602 \times 10^{-19} \text{ C}$$
$$m_e = 9.109 \times 10^{-31} \text{ kg}$$
$$h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s}$$
$$k = 1.381 \times 10^{-23} \text{ J/K}$$
$$\varepsilon_0 = 8.854 \times 10^{-12} \text{ C}^2/(\text{N} \cdot \text{m}^2)$$
$$c = 3.00 \times 10^8 \text{ m/s}$$
$$e \approx 1.6 \times 10^{-19} \text{ C}$$
$$kT \approx 0.026 \text{eVat} T = 300\text{K}$$

Formulae

$kT_{temp} = 0.026(\frac{temp}{300})$, kT at a temperature temp
$\sigma = en\mu_n + ep\mu_p$, Conduction
$n_i^2 = n_0 p_0$, concentration at equilibrium
$n_i^2 = n_c n_v e^{-E_g/kT}$,
$n_i^2 \propto T^3 e^{-E_g/kT}$, proportionality ratio
$n_i^2 at500 = (\frac{500}{300})^3 e^{-E_g/kTat500} e^{E_g/kTat300}$, proportional temp
$E = \frac{hc}{\lambda}$, energy of photon
$E_g = E_c - E_v$, Energy band gap
$f(E) = \frac{1}{1+e^{\frac{E-E_f}{kT}}}$, Fermi-Dirac Distribution Function
$n = N_c \cdot e^{-\frac{E_c - E_f}{kT}}$, Electron carrier concentration
$p = N_v \cdot e^{-\frac{E_f - E_v}{kT}}$, Hole carrier concentration
$J_d = q \cdot n \cdot \mu_n \cdot E$, Drift Current
$J_n = q \cdot D_n \cdot \frac{dn}{dx}$, Diffusion Current
$E_g = E_c - E_v$, Energy-Band Gap (Eg)
$\frac{1}{m^*} = \frac{1}{m_l} + \frac{1}{m_t}$, Electron and Hole Effective Mass
$q = 1.602 \times 10^{-19}$ C, Charge of an Electron
$n = N_c \cdot e^{-\frac{E_c - E_f}{kT}}$, Electron Carrier Concentration
$p = N_v \cdot e^{-\frac{E_f - E_v}{kT}}$, Hole Carrier Concentration
$J_n = q \cdot n \cdot \mu_n \cdot E$, Drift Current Density for Electrons
$J_p = q \cdot p \cdot \mu_p \cdot E$, Drift Current Density for Holes
$J_n = q \cdot D_n \cdot \frac{dn}{dx}$, Diffusion Current Density for Electrons
$J_p = q \cdot D_p \cdot \frac{dp}{dx}$, Diffusion Current Density for Holes
$N_c = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}$, Density of States in the Conduction Band (Nc)
$N_v = 2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}$, Density of States in the Valence Band (Nv)
$P_0 = n_i e^{\frac{E_{fi} - E_f}{kT}}$
$P_0 = \frac{N_A - N_D}{2} + \sqrt{(\frac{N_A - N_D}{2})^2 + n_i^2}$
$N_0 = \frac{N_D - N_A}{2} + \sqrt{(\frac{N_D - N_A}{2})^2 + n_i^2}$
$f_F(E) = \frac{1}{1+e^{\frac{E-E_f}{kT}}}$, Fermi-Dirac Distribution Function
$f_F(E) = e^{\frac{-(E-E_f)}{kT})}$, Boltzman Approximation when $E - E_F >> kT$
$\mu_n = \frac{q \cdot \tau_n}{m^*}$, Electron Mobility
$\mu_p = \frac{q \cdot \tau_p}{m^*}$, Hole Mobility
$G = \alpha \cdot I$, Generation Rate of Electron-Hole Pairs
$R = B \cdot np - A \cdot n_i^2$, Recombination Rate
$\frac{\partial n}{\partial t} + \nabla \cdot \mathbf{J}_n = G - R$, Continuity Equation for Electron Current
$\frac{\partial p}{\partial t} - \nabla \cdot \mathbf{J}_p = G - R$, Continuity Equation for Hole Current
$P_0 + N_D = n_0 + N_A$, Charge neutrality
$J_{drf} = en\mu_n E + ep\mu_p E = \sigma E$, Total Drift
$I = AJ_{drf}$, Current
$E = Volt/Len$, Electric Field
$V_{dn} = \mu_n E$, Drift velocity for electrons
$V_{dp} = \mu_p E$, Drift velocity for holes

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$A_v = \frac{V_{out}}{V_{in}}$, Voltage Gain Formula
$|A_v| = gmR_D$,
$A_v = \frac{R_D}{1/gm}$,
$V_{ov} = V_{bias} - V_{th}$, Overdrive Voltage
$g_m = K_n' \frac{W}{L} V_{ov}$, transconductance parameter
$g_m = \frac{2I_D}{V_{ov}}$
$I_D = \frac{1}{2} gmV_{ov}$, Drain Current Equation
$I_D = \frac{1}{2} K_n' \frac{W}{L} V_{ov}^2$, Drain Current Equation
$V_{ov} = \frac{I_D}{K_n' \cdot \frac{W}{L}}$, Overdrive voltage
$I_D = gm \cdot V_{gs}$, Drain current
$I_D = \frac{V_{DD}}{R_D}$, Drain current
$g_m = \frac{\Delta I_D}{\Delta V_{GS}} = K_n' \frac{W}{L} V_{ov}$,
$V_{DD} = V_{DS} + I_D \cdot R_D$, Load line equation
$V_{DD} = V_{DS} + I_D \cdot R_D$, Load line equation
$r_o = \frac{V_A}{I_D}$, Early voltage V_A
$V_A' = \frac{V_A}{L}$, early voltage process parameter $= 20V/\mu m$
$A_o = gm \cdot r_o$, Intrinsic gain for bjt and mosfet
$A_o = \frac{2V_A}{V_{ov}}$, Intrinsic gain
$A_o = \frac{2V_A' L}{V_{ov}}$, Intrinsic gain

Proportionalities

$I_D \propto V_{ov}^2$, drain current and overdrive voltage proportionality

§1.2 - The PN Junction

Notes

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.
When $N_A >> N_D$, the semiconductor is p-type.
When $N_D >> N_A$, the semiconductor is n-type.

BJT Amplifier

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

Transistor DC Equivalent

$V_{th} = \frac{V_{cc}}{R_1 + R_2} \cdot R_2$,
$R_{th} = R_1 || R_2$,
$V_{ce}(sat) \approxeq 0.2(typ)$,
$I_E \approxeq I_C$, 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}
$I_{RE} = I_B(\beta + 1)R_E$,

Transistor formulas

$I_C = \beta \cdot I_B$, Conduction Parameter
$I_C = I_S e^{\frac{V_{BE}}{V_T}}$,
$I_B = \frac{I_E}{\beta + 1}$,
$\alpha = \frac{I_C}{I_E}$, 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

MOS Field-Effect Transistor

N-Channel

$v_{DS}(sat) = v_{GS} - V_{TN}$, 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.
$\epsilon_{ox} = (3.9)(8.85 \times 10^{-14}\,\text{F/cm})$, 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

$i_D = K_p\left[2(v_{SG} - V_{TP})v_{SD} - v_{SD}^2\right]$, 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
$k_p' = \mu_p C_{ox}$

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

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

Integration by Parts

$$\int udv = uv - \int vdu$$

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:

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