EE 2200 INTRO. TO ELECTRONIC DEVICES

ECE, Missouri S&T

WORKSHEETS
FOR
EXAMINATION 1

Topics Include:
Definitions
Semiconductor Crystals
Carriers and Doping (Resistivity)
Drift and Diffusion Currents and Junction
Diodes and Diode Circuits

Boltzmann's constant:	$k = 1.381 \times 10^{-23}$ J/K = 8.618×10^{-5} eV/K		
Planck's constant	$h = 4.136 \times 10^{-15}$ eV-sec = 6.626×10^{-34} J-sec		
Electronic charge:	$q = 1.602 \times 10^{-19}$ C		
kT at 300 K	kT = 0.0259 eV	eV-J conversion	1 eV = 1.602×10^{-19} J
Free-space permittivity	$\varepsilon_o = 8.854 \times 10^{-14}$ F/cm	Speed of Light	$c = 2.998 \times 10^{10}$ cm/s
Relative permittivity	Si: 11.9	Ge: 16.0	GaAs: 13.1
Bandgap energies	Si: 1.12 eV	Ge: 0.67 eV	GaAs: 1.42 eV

Semiconductor Example

Consider a Si crystal which is doped with 10^{12} phosphorous (P) atoms/cm^3 and with 10^{13} aluminum (Al) atoms/cm^3. Assume all of the dopants are ionized and that the semiconductor is at room temperature.

Identify the dopants as donors and/or acceptors.

Host Si (col IV). P is col V, hence it is a donor
Al is col III, hence it is an acceptor.

Calculate the equilibrium electron and hole concentrations.

($N_a^- > N_d^+$), hence the majority carrier will be holes
The equations are

$$n_0 + N_a^- = p_0 + N_d^+ \qquad n_0 p_0 = n_i^2$$

Solve for the majority carrier p_0. Substitute for a single equation in p_0.

$$p_0 - (N_a^- - N_d^+) - n_0 = 0 \qquad n_0 = n_i^2/p_0$$

$$p_0 - (N_a^- - N_d^+) - (n_i^2/p_0) = 0 \quad \text{or} \quad p_0^2 - (0.9\text{x}10^{13})\, p_0 - (n_i^2) = 0$$

Taking the physical solution of this quadratic equation.

$$p_0 = -(1/2)[-(0.9\text{x}10^{13}) + (1/2)\sqrt{\{[-(0.9\text{x}10^{13})]^2 - 4\,(-\,n_i^2)\}}$$

$$p_0 = (1/2)(0.9\text{x}10^{13}) + (1/2)\sqrt{[(0.9\text{x}10^{13})^2 + 4\,(1.5\text{x}10^{10})^2]}$$

$$p_0 = 9.00 \text{ x } 10^{12} \text{ cm}^{-3} \ (= 9.000025 \text{ x } 10^{12} \text{ cm}^{-3})$$

The minority carrier concentration is

$$n_0 = n_i^2/p_0 = (1.5 \text{ x } 10^{10})^2/(9.00 \text{ x } 10^{12}) = 2.50 \text{ x } 10^7 \text{ cm}^{-3}$$

Calculate the Fermi level.

The equation in terms of p_o is

$$(E_F - E_i) = -\,kT\ \text{In}(p_o/n_i)$$

$$(E_F - E_i) = -\,(0.0259 \text{ eV})\ \ln[(9.00 \text{ x } 10^{12})/(1.5 \text{ x } 10^{10})] = -\,0.1657 \text{ eV}$$

Calculate the resistivity given mobilities of μ_n = 1450 cm^2/Vs and μ_p = 500 cm^2/Vs.

$$\rho = 1/\sigma = [q(n_0\mu_n + p_0\mu_p)]^{-1}$$

$$\rho = 1/\{(1.602 \text{ x } 10^{-19})[(2.50 \text{ x } 10^7)(1450) + (9.00 \text{ x } 10^{12})(500)]\}$$

$$\rho = 1{,}387\ (\Omega\text{-cm})$$

Semiconductor Example

Consider a Si crystal which is doped with 10^{12} phosphorous (P) atoms/cm^3 and with 10^{13} aluminum (Al) atoms/cm^3. Assume all of the dopants are ionized and that the semiconductor is at room temperature.

Identify the dopants as donors and/or acceptors.

Calculate the equilibrium electron and hole concentrations.

Calculate the Fermi level.

Calculate the resistivity given mobilities of $\mu_n = 1450$ cm^2/Vs and $\mu_p = 500$ cm^2/Vs.

Semiconductor Example

Consider a Si crystal with a Fermi level of $(E_F - E_i) = 0.200$ eV. The dimensions are length 5 mm, width 1 mm, and height 1 mm. Assume that the semiconductor is at room temperature.

Is the semiconductor n-type or p-type and why?

The semiconductor is n-type since the Fermi level is positive (e.g. above E_i).

Calculate the equilibrium electron and hole concentrations.

The equation in terms of n_o is

$(E_F - E_i) = kT\ \mathrm{In}(n_o/n_i)$ or $n_o = n_i \exp[(E_F - E_i)/kT]$

$n_o = (1.5 \times 10^{10}) \exp[(0.200\text{ eV})/(0.0259\text{ eV}] = 3.39 \times 10^{13}\text{ cm}^{-3}$

Then,

$p_0 = n_i^2/n_0 = (1.5 \times 10^{10})^2/(3.39 \times 10^{13}) = 6.64 \times 10^6\text{ cm}^{-3}$

What are the doping concentrations?

Insufficient information is given to calculate the doping concentrations. However, the effective doping concentration from $n_0 + N_a^- = p_0 + N_d^+$ is

$(N_d^+ - N_a^-) = n_0 - p_0 \sim 3.39 \times 10^{13}\text{ cm}^{-3}$

Calculate the resistivity given mobilities of $\mu_n = 1450$ cm² /Vs and $\mu_p = 500$ cm² /Vs.

$\rho = 1/\sigma = [q(n_0\mu_n + p_0\mu_p)]^{-1}$

$\rho = 1/\{(1.602 \times 10^{-19})[(3.39 \times 10^{13})(1450) + (6.64 \times 10^6)(500)]\}$

$\rho = 1/0.007866 = 127\ (\Omega\text{-cm})$

Calculate the resistance.

The resistance is

$R = (L/A)\ \rho = [0.5\text{ cm}/(0.1\text{ cm})(0.1\text{ cm})]\ 127\ (\Omega\text{-cm}) =$

$R = 6{,}357\ \Omega$

Semiconductor Example

Consider a Si crystal with a Fermi level of $(E_F - E_i) = 0.200$ eV. The dimensions are length 5 mm, width 1 mm, and height 1 mm. Assume that the semiconductor is at room temperature.

Is the semiconductor n-type or p-type and why?

Calculate the equilibrium electron and hole concentrations.

What are the doping concentrations?

Calculate the resistivity given mobilities of $\mu_n = 1450$ cm^2/Vs and $\mu_p = 500$ cm^2/Vs.

Calculate the resistance.

Junction Example

Consider abrupt pn junctions made of Si and Ge. Assume RT. Doping values are

$N_{ap}^- = 10^{16}$ cm^{-3} and $N_{dp}^+ = 0$ on the p side and

$N_{dn}^+ = 10^{16}$ cm^{-3} and $N_{an}^- = 0$ on the n side.

Calculate the contact potential V_o values in volts and energy difference qV_o values in eV for Si and Ge.

For extrinsic doping, the contact potential is

$V_0 = (kT/q) \ln[(N_{ap}^- - N_{dp}^+)(N_{dn}^+ - N_{an}^-)/n_i^2]$

Note that kT = 0.0259 eV, 1 C x 1 V = 1 J, and 1 eV = 1.602 x 10^{-19} J, then

$kT/q = [(0.0259 \text{ eV}) \times (\cancel{1.602 \times 10^{-19}} \text{ J} / 1 \text{ eV})] \times (1/\cancel{1.602 \times 10^{-19}} \text{ C})$

$kT/q = 0.0259$ J/C = **0.0259 V**

For a Silicon Junction,

$V_0 = (0.0259 \text{ V}) \ln[(10^{16} - 0)(10^{16} - 0)/(1.5 \times 10^{10})^2]$

$V_0 = (0.0259 \text{ V}) \ln[4.444 \times 10^{11}] =$ **0.695 V**

$qV_0 = \{[(\cancel{1.602 \times 10^{-19}}) \times (0.695)] \text{ J}\} \times (1 \text{ eV} / \cancel{1.602 \times 10^{-19}} \text{ J}) =$ **0.695 eV**

For a Germanium Junction,

$V_0 = (0.0259 \text{ V}) \ln[(10^{16} - 0)(10^{16} - 0)/(2.3 \times 10^{13})^2]$

$V_0 = (0.0259 \text{ V}) \ln[1.89 \times 10^{5}] =$ **0.315 V**

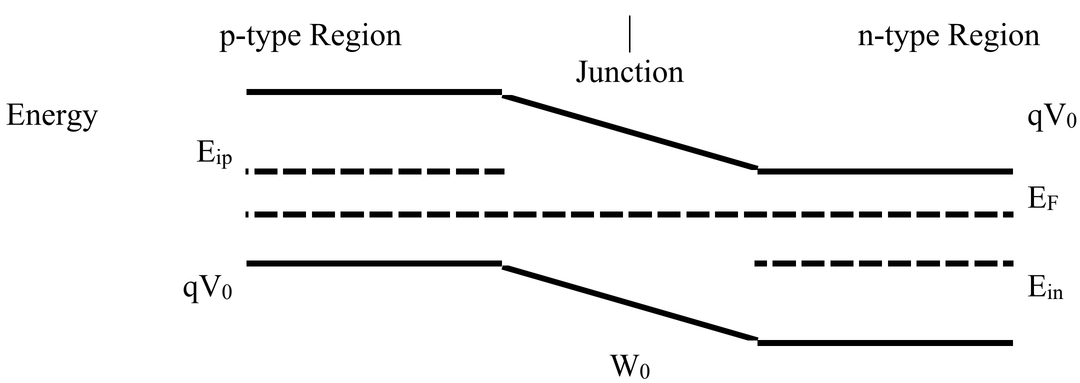
$qV_0 = \{[(\cancel{1.602 \times 10^{-19}}) \times (0.315)] \text{ J}\} \times (1 \text{ eV} / \cancel{1.602 \times 10^{-19}} \text{ J}) =$ **0.315 eV**

State the trend contact potential with respect to E_G.

Si E_G =1.12 eV and Ge E_G = 0.67 eV

As E_G increases (and n_i decreases), the contact potential V_0 increases.

For abrupt pn junctions with $(N_{ap}^- - N_{dp}^+) = (N_{dn}^+ - N_{an}^-)$, sketch the equilibrium band diagram including the Fermi level, E_{ip}, E_{in}, and the energy difference qV_o.



Junction Example

Consider abrupt pn junctions made of Si and Ge. They are doped with

$N_{ap}^{-} = 10^{16}$ cm^{-3} and $N_{dp}^{+} = 0$ on the p side and

$N_{dn}^{+} = 10^{16}$ cm^{-3} and $N_{an}^{-} = 0$ on the n side.

Calculate the contact potential V_o values in volts and energy difference qV_o values in eV for Si and Ge.

State the trend contact potential with respect to E_G.

For abrupt pn junctions with $(N_{ap}^{-} - N_{dp}^{+}) = (N_{dn}^{+} - N_{an}^{-})$, sketch the equilibrium band diagram including the Fermi level, E_{ip}, E_{in}, and the energy difference qV_o.

Junction Example

Consider an abrupt Si junction with only $N_{ap}^{-} = 10^{17}$ cm^{-3} on the p side and only $N_{dn}^{+} = 10^{13}$ cm^{-3} on the n side. Assume that the semiconductor is at room temperature.

Calculate the contact potential.

For extrinsic doping, the contact potential is

$V_0 = (kT/q) \ln[(N_{ap}^{-} - N_{dp}^{+})(N_{dn}^{+} - N_{an}^{-})/n_i^2]$

$V_0 = (0.0259 \text{ V}) \ln[(10^{17} - 0)(10^{13} - 0)/(1.5 \times 10^{10})^2]$

$V_0 = (0.0259 \text{ V}) \text{In}[4.444 \times 10^{9}]$

$V_0 = 0.575 \text{ V}$

Calculate the Fermi levels.

For the p side

$(E_F - E_{ip}) = - kT \text{ In}(p_o/n_i)$

$(E_F - E_{ip}) = - (0.0259 \text{ eV}) \ln[(10^{17})/(1.5 \times 10^{10})] = - 0.4070 \text{ eV}$

For the n side

$(E_F - E_{in}) = kT \text{ In}(_o/n_i)$

$(E_F - E_{in}) = (0.0259 \text{ eV}) \ln[(10^{13})/(1.5 \times 10^{10})] = 0.1684 \text{ eV}$

Note that

$(E_{ip} - E_{in}) = - (E_F - E_{ip}) + (E_F - E_{in}) = 0.407 + 0.168 = 0.575 \text{ eV}$

$(E_{ip} - E_{in}) = qV_o = 0.575 \text{ eV}$

Note if $V_0 = X$ (in V),

then $qV_o = (1.602 \times 10^{-19})(X)$ J

and $qV_o = (1.602 \times 10^{-19})(X) \text{ J } (1 \text{ eV})/(1.602 \times 10^{-19}) = X$ eV

Calculate the ratio of x_{no} / x_{po}.

The charge density relationship is

$|Q_-| = |Q_+|$; $(N_{ap}^{-} - N_{dp}^{+}) A x_{p0} = (N_{dn}^{+} - N_{an}^{-}) A x_{n0}$;

or $(N_{ap}^{-})_{Eff}\, x_{p0} = (N_{dn}^{+})_{Eff}\, x_{n0}$;

$x_{n0} / x_{p0} = (N_{ap}^{-})_{Eff} / (N_{dn}^{+})_{Eff} = (10^{17} - 0)/(10^{13} - 0) = 10{,}000$

Junction Example

Consider an abrupt Si junction with only $N_{ap}^{-} = 10^{17}$ cm^{-3} on the p side and only $N_{dn}^{+} = 10^{13}$ cm^{-3} on the n side. Assume that the semiconductor is at room temperature.

Calculate the contact potential.

Calculate the Fermi levels.

Calculate the ratio of x_{no} / x_{po}.

Junction Example

Consider an abrupt Si junction with $N_{ap}^- = 10^{16}$ cm^{-3} and $N_{dp}^+ = 10^{15}$ cm^{-3} on the p side and only $N_{dn}^+ = 10^{15}$ cm^{-3} on the n side. Assume that the semiconductor is at room temperature.

Calculate the contact potential.

For extrinsic doping, the contact potential is

$$V_0 = (kT/q)\ \ln[(N_{ap}^- - N_{dp}^+)(N_{dn}^+ - N_{an}^-)/n_i^2]$$

$$V_0 = (0.0259\text{ V})\ \ln[(10^{16} - 10^{15})(10^{15} - 0)/(1.5 \text{ x } 10^{10})^2]$$
$$V_0 = (0.0259\text{ V})\ \text{In}[4.000 \text{ x } 10^{10}]$$
$$V_0 = 0.632\text{ V}$$

Calculate the depletion width W_0 at equilibrium.

For equilibrium, the depletion width is (note for Si $\varepsilon_r = 11.8$)

$$W_0 = \{[2\varepsilon_r\varepsilon_0\ (V_0)/q]\ [(N_{ap}^-)_{Eff} + (N_{dn}^+)_{Eff}\ ] / [(N_{ap}^-)_{Eff}\ (N_{dn}^+)_{Eff}\ ]\}^{1/2}$$
$$W_0 = \{[2(11.8)(8.854 \text{ x } 10^{-14})(0.632)/(1.602 \text{ x } 10^{-19})]\ [(10^{16} - 10^{15}) + (10^{15} - 0)]/[(10^{16} - 10^{15})(10^{15} - 0)]\}^{1/2}$$
$$W_0 = 0.957 \text{ x } 10^{-4}\text{ cm} = 0.957\ \mu\text{m}$$

Calculate the equilibrium depletion values x_{no} and x_{po}.

The charge density relationship is $|Q_-| = |Q_+|$

$$(N_{ap}^- - N_{dp}^+)\ Ax_{p0} = (N_{dn}^+ - N_{an}^-)\ Ax_{n0} \quad \text{or} \quad (N_{ap}^-)_{Eff}\ x_{p0} = (N_{dn}^+)_{Eff}\ x_{n0}$$
$$x_{n0} = [(N_{ap}^-)_{Eff} / (N_{dn}^+)_{Eff}]\ x_{p0} = [(10^{16} - 10^{15})/(10^{15} - 0)]\ x_{p0} = 9\ x_{p0}$$

Then $W_0 = x_{p0} + x_{n0} = x_{p0} + 9x_{p0} = 10x_{p0}$

$$x_{p0} = (1/10)\ W_o = 0.0957\ \mu\text{m}$$
$$x_{n0} = 9\ x_{p0} = 0.862\ \mu\text{m}$$

Calculate the depletion width W for a reverse bias of $V = -100$ V.

For the junction under bias, the depletion width is (note for Si $\varepsilon_r = 11.8$)

$$W = \{[2\varepsilon_r\varepsilon_0\ (V_0 - V)/q]\ [(N_{ap}^-)_{Eff} + (N_{dn}^+)_{Eff}\ ] / [(N_{ap}^-)_{Eff}\ (N_{dn}^+)_{Eff}\ ]\}^{1/2}$$
$$W = \{[2(11.8)(8.854 \text{ x } 10^{-14})(0.632 + 100)/(1.602 \text{ x } 10^{-19})]\ [(10^{16} - 10^{15}) + (10^{15} - 0)]/[(10^{16} - 10^{15})(10^{15} - 0)]\}^{1/2}$$
$$W = 12.1 \text{ x } 10^{-4}\text{ cm} = 12.1\ \mu\text{m}$$

Junction Example

Consider an abrupt Si junction with $N_{ap}^{-} = 10^{16}$ cm^{-3} and $N_{dp}^{+} = 10^{15}$ cm^{-3} on the p side and only $N_{dn}^{+} = 10^{15}$ cm^{-3} on the n side. Assume that the semiconductor is at room temperature.

Calculate the contact potential.

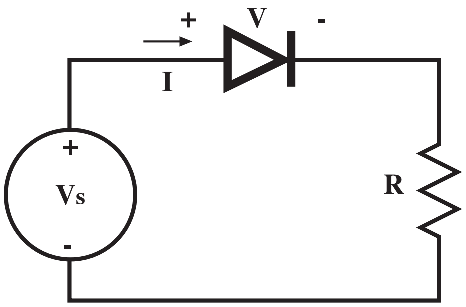
Calculate the depletion width W_0 at equilibrium.

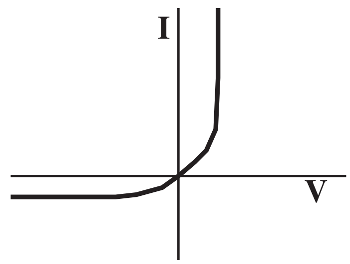
Calculate the equilibrium depletion values x_{no} and x_{po}.

Calculate the depletion width W for a reverse bias of $V = - 100$ V.

Diode Biasing Example

Consider the following circuit with a source voltage $V_S = 5.0 \sin(10t)$ V, a load resistor R = 1.00 kΩ, and diode IV characteristics of turn-on voltage $V_{to} = 0.7$ V and reverse saturation current of $I_0 = 0.01$ mA.





Calculate the maximum voltage and current for forward bias, i.e. the diode is on.

The diode is forward biased when $V_S = +5$ V
For forward bias (away from the knee of the IV curve), the diode voltage is

$$V_{max} = V_{to} = 0.7 \text{ V}$$

By the load line equation (from KVL) the current is

$$I_{max} = (1/R)[V_S - (V_{to})] = (1/1000)[5.0 - 0.7] = 4.3 \text{ mA}$$

Calculate the voltage across the resistor for this maximum condition.

By Ohm's Law

$$V_{Rmax} = I_{max} R = (4.3 \text{ mA})\ (1000\ \Omega) = 4.3 \text{ V}$$

Calculate the minimum voltage and current for reverse bias, i.e. the diode is off.

The diode is reverse biased when $V_S = -5$ V
For reverse bias (away from the knee of the IV curve), the diode current is

$$I_{min} = -\ I_0 = -\ 0.01 \text{ mA}$$

By the load line equation (from KVL) the voltage is

$$V_{min} = V_S - (I_{min})R = V_S - (-\ I_0)R = -\ 5.0 - (-0.01 \text{ mA})(1000\ \Omega)$$

$$V_{min} = -\ 4.99 \text{ V}$$

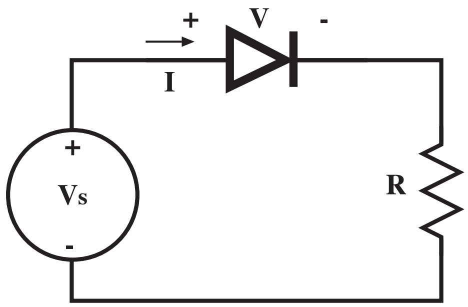
Calculate the voltage across the resistor for this minimum condition.

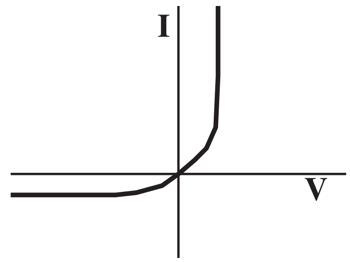
By Ohm's Law

$$V_{Rmin} = I_{min} R = (-\ 0.01 \text{ mA})\ (1000\ \Omega) = -\ 0.01 \text{ V}$$

Diode Biasing Example

Consider the following circuit with a source voltage $V_S = 5.0 \sin(10t)$ V, a load resistor R = 1.00 kΩ, and diode IV characteristics of turn-on voltage $V_{to} = 0.7$ V and reverse saturation current of $I_0 = 0.01$ mA.





Calculate the maximum voltage and current for forward bias, i.e. the diode is on.

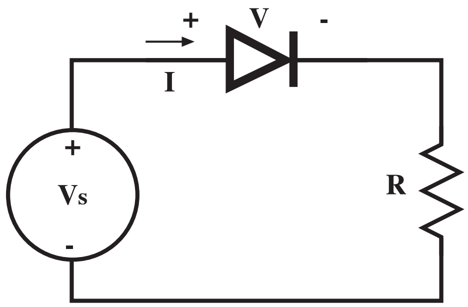
Calculate the voltage across the resistor for this maximum condition.

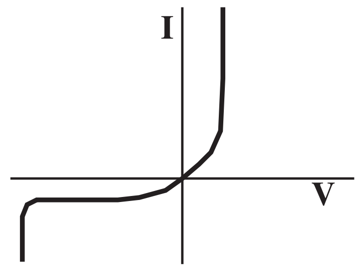
Calculate the minimum voltage and current for reverse bias, i.e. the diode is off.

Calculate the voltage across the resistor for this minimum condition.

Breakdown Diode Biasing Example

Consider the following diode circuit with a constant source voltage V_S, a load resistor R = 1.00 kΩ, and diode IV characteristics of turn-on voltage $V_{to} = 0.7$ V, reverse saturation current of $I_0 = 0.01$ mA, and a breakdown voltage $V_{br} = 26$ V.





Calculate the operating point if V_S = - 25 V. Is the diode forward biased or reverse biased?

The diode is reverse biased
For reverse bias the diode can be in breakdown or not in breakdown.
Assume that the diode is not in breakdown, then

$I = - I_0 = - 0.01$ mA

By the load line equation (from KVL) the voltage is

$V = V_S – (- I_0)R = - 25.0 – (-0.01 \text{ mA})(1000\ \Omega) = -24.99$ V

These values are possible
Note that if the diode is assumed to be in breakdown: $V = - V_{br} = - 26$ V and

$I = (1/R)[V_S – (- V_{br})] = (- 25 +26)/1000 = 1$ mA
But, the current cannot be greater than $- I_0$ in reverse bias.
The values are not possible

Calculate the operating point if V_S = - 30 V.

Note that the LL intercepts are $I = 0$ for $V = V_S$ and $V = 0$ for $I = V_S /R$
Based on the I=0 intercept, the diode should be in breakdown. Hence,

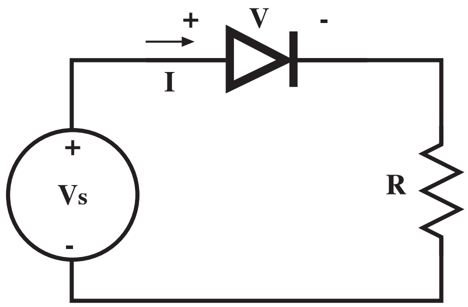
$V = - V_{br} = - 26$ V

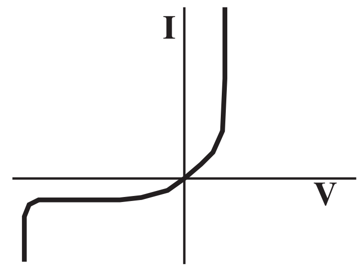
By the load line equation (from KVL) the current is

$I = (1/R)[V_S – (-V_{br})] = (1/1000)[-30 – (-26)] = - 4.0$ mA
Note that these values are possible.
(If the diode is incorrectly assumed to be not in breakdown,
the result voltage value will be less than $-V_{br}$ which is not possible.)

Breakdown Diode Biasing Example

Consider the following diode circuit with a constant source voltage V_S, a load resistor R = 1.00 kΩ, and diode IV characteristics of turn-on voltage V_{to} = 0.7 V, reverse saturation current of I_0 = 0.01 mA, and a breakdown voltage V_{br} = 26 V.



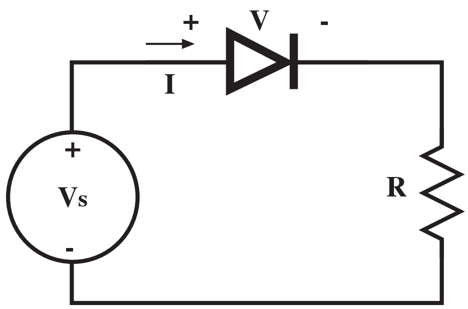


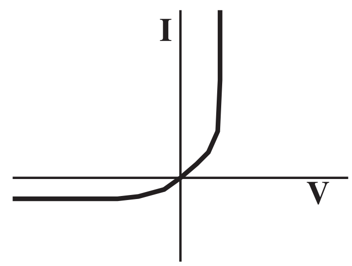
Calculate the operating point if V_S = - 25 V. Is the diode forward biased or reverse biased?

Calculate the operating point if V_S = - 30 V.

Diode Biasing Example

Consider the following circuit with a constant source voltage V_S, an unknown load resistance R, and diode IV characteristics of turn-on voltage V_{to} = 0.70 V and reverse saturation current of I_0 = 0.01 mA.





Calculate the diode current for which the voltage is V = - 0.070 V. Use the low-level-injection diode equation and assume room temperature.

The diode is reverse biased for a negative voltage.
The diode equation is $I = I_0[\exp(qV/kT) - 1]$
Then,

$$I = 0.01 \text{ mA } [\exp(-0.070 \text{ V}/0.0259 \text{ V}) - 1] = - 0.00933 \text{ mA}$$

Note that this current is $I = - 0.0933\ I_0$.

If the source voltage is V_S = +4.0 V, calculate the required resistance for a diode current of I = + 2.0 mA.

The diode is forward biased when V_S = +4.0 V.
For forward bias (away from the knee of the IV curve), the diode voltage is

$$V = V_{to} = 0.7 \text{ V}$$

The load line equation is

$$-V_S + V + IR = 0$$

The required resistance is

$$R = (1/I)[V_S - (V_{to})] = (1/0.002 \text{ A})[4.0 - 0.7 \text{ V}] = 1.65 \text{ k}\Omega.$$

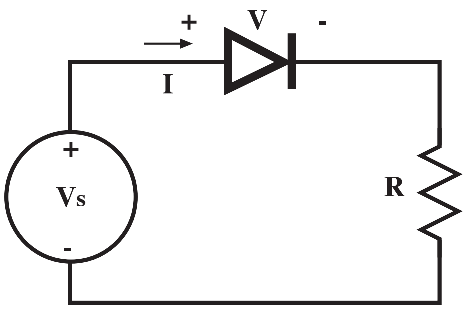
If the source voltage is V_S = +4.0 V, calculate the required resistance for a diode current of I = + 4.0 mA.

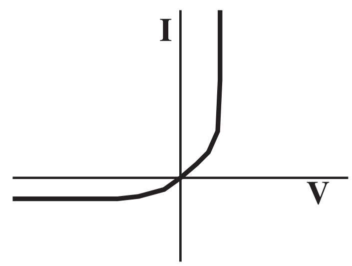
The required resistance is

$$R = (1/I)[V_S - (V_{to})] = (1/0.004 \text{ A})[4.0 - 0.7 \text{ V}] = 0.825 \text{ k}\Omega.$$

Diode Biasing Example

Consider the following circuit with a constant source voltage V_S, an unknown load resistance R, and diode IV characteristics of turn-on voltage V_{to} = 0.70 V and reverse saturation current of I_0 = 0.01 mA.





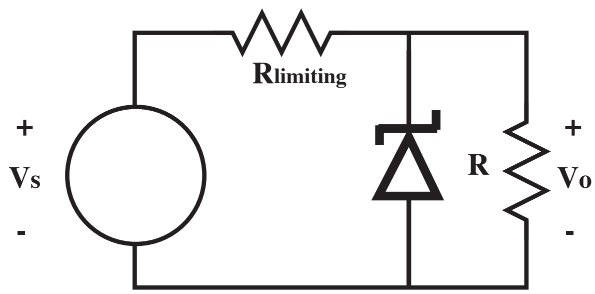
Calculate the diode current for which the voltage is V = - 0.070 V. Use the low-level-injection diode equation and assume room temperature.

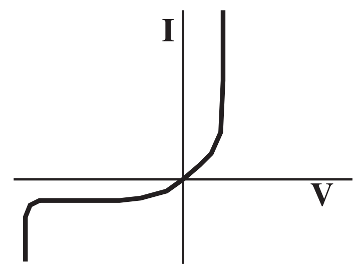
If the source voltage is V_S = +4.0 V, calculate the required resistance for a diode current of I = + 2.0 mA.

If the source voltage is V_S = +4.0 V, calculate the required resistance for a diode current of I = + 4.0 mA.

Diode Limiter Example

Consider the following limiting circuit with a source voltage V_S, resistances $R_{limiting} = R = 1.0\ k\Omega$, and diode IV characteristics of turn-on voltage $V_{to} = 0.70$ V, breakdown voltage $V_{br} = 10$ V, and reverse saturation current of $I_0 = 0.10$ mA.





If the source voltage is a square wave that varies between $V_{S,Max} = +30.0$ V and $V_{S,Min} = +10.0$ V, calculate the load voltage V_0 for the minimum input level.

The diode is reverse biased when $V_S = +10.0$ V.
For reverse bias (away from the knee of the IV curve), the diode may be in breakdown or not in breakdown. Consider a calculation of the diode voltage assuming that the diode did not have a breakdown point. If the calculated diode voltage is greater or equal to the breakdown voltage, then the diode is not in breakdown. If the calculated diode voltage is less than the breakdown voltage, the assumption is incorrect and the diode is in breakdown.
Assuming that the diode is not in breakdown, the diode current is $I = - I_0$.
The load voltage V_0 can be calculated from the KCL equation

$$V_0/R - I + (V_0 - V_S)/R_{limiting} = 0$$

$$V_0 = (1/2)\ R\ I + (1/2)\ V_S = (1/2)(1000)(-\ 0.0001) + (1/2)\ 10 = 4.95\ V$$

Note that by KVL the diode voltage is $V = - V_0 = - 4.95\ V > - V_{br}$.
The assumption was correct.
$V_0 = + 4.95$ V (Diode is Reverse Biased with no Breakdown)

If the source voltage is a square wave that varies between $V_{S,Max} = +30.0$ V and $V_{S,Min} = +10.0$ V, calculate the load voltage V_0 for the maximum input level.

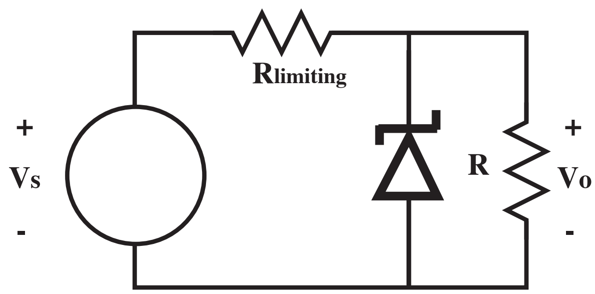
The diode is reverse biased when $V_S = +30.0$ V.
Assuming that the diode is in breakdown, the diode voltage is $V = - V_{br}$.
By KVL, the load voltage is $V_0 = - V = - (-10\ V)$
The KCL equation gives

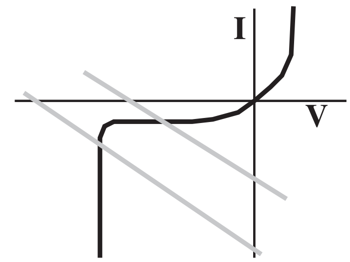
$$I = V_0/R + (V_0 - V_S)/R_{limiting} = [2(10) - 30]/(1000) = -10\ mA$$

Note that the diode current is $I < - I_0$, the assumption was correct.
$V_0 = + 10$ V (Diode is Reverse Biased with Breakdown)

Diode Limiter Example

Consider the following limiting circuit with a source voltage V_S, resistances $R_{limiting} = R = 1.0\ k\Omega$, and diode IV characteristics of turn-on voltage $V_{to} = 0.70$ V, breakdown voltage $V_{br} = 10$ V, and reverse saturation current of $I_0 = 0.10$ mA.





If the source voltage is a square wave that varies between $V_{S,Max} = +30.0$ V and $V_{S,Min} = +10.0$ V, calculate the load voltage V_0 for the minimum input level.

KVL gives $V_0 = - V$ and KCL gives $V_0/R - I + (V_0 - V_S)/R_{limiting} = 0$.
With $R_{limiting} = R$, $- V_0/R - I + (-V - V_S)/R = 0$ or $V = - (1/2)\ V_S - (1/2)\ R\ I$.
For $V_{S,Min} = +10.0$ V, the voltage intercept is $- (1/2)\ V_S = -5\ V > - V_{br}$.
Hence, the KCL equation intersects the IV characteristic in the reverse bias (no breakdown region).
Then, $I = - I_0$ and the KCL equation gives
$V_0 = (1/2)\ R\ I + (1/2)\ V_S = (1/2)(1000)(- 0.0001) + (1/2)\ 10 = 4.95$ V

$V_0 = + 4.95$ V (Diode is Reverse Biased with no Breakdown)

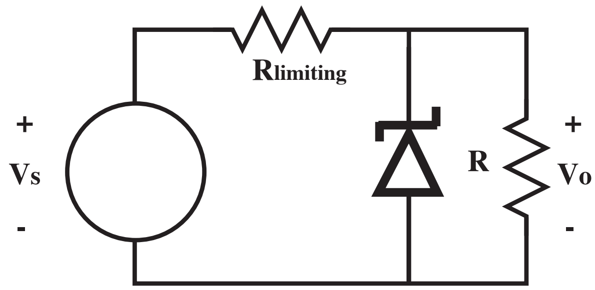
If the source voltage is a square wave that varies between $V_{S,Max} = +30.0$ V and $V_{S,Min} = +10.0$ V, calculate the load voltage V_0 for the maximum input level.

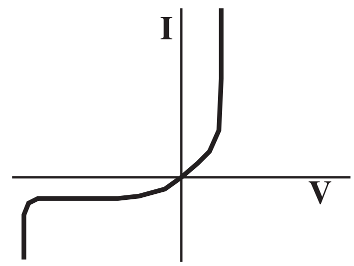
KVL gives $V_0 = - V$ and KCL gives $V_0/R - I + (V_0 - V_S)/R_{limiting} = 0$.
With $R_{limiting} = R$, $- V_0/R - I + (-V - V_S)/R = 0$ or $V = - (1/2)\ V_S - (1/2)\ R\ I$.
For $V_{S,Max} = +30.0$ V, the voltage intercept is $- (1/2)\ V_S = -15\ V < - V_{br}$.
Hence, the KCL equation intersects the IV characteristic in the reverse bias with breakdown region.
Then, $V_0 = - V = - (- V_{br}) = 15$ V and the KCL equation gives
$I = V_0/R + (V_0 - V_S)/R_{limiting} = [2(10) - 30]/(1000) = -10$ mA

$V_0 = + 10$ V (Diode is Reverse Biased with Breakdown)

Diode Limiter Example

Consider the following limiting circuit with a source voltage V_S, resistances $R_{limiting} = R = 1.0\ k\Omega$, and diode IV characteristics of turn-on voltage $V_{to} = 0.70$ V, breakdown voltage $V_{br} = 10$ V, and reverse saturation current of $I_0 = 0.10$ mA.





If the source voltage is a square wave that varies between $V_{S,Max} = +30.0$ V and $V_{S,Min} = +10.0$ V, calculate the load voltage V_0 for the minimum input level.

If the source voltage is a square wave that varies between $V_{S,Max} = +30.0$ V and $V_{S,Min} = +10.0$ V, calculate the load voltage V_0 for the maximum input level.

EE 2200 INTRO. TO ELECTRONIC DEVICES

ECE, Missouri S&T **@ 2023 Steve E. Watkins**

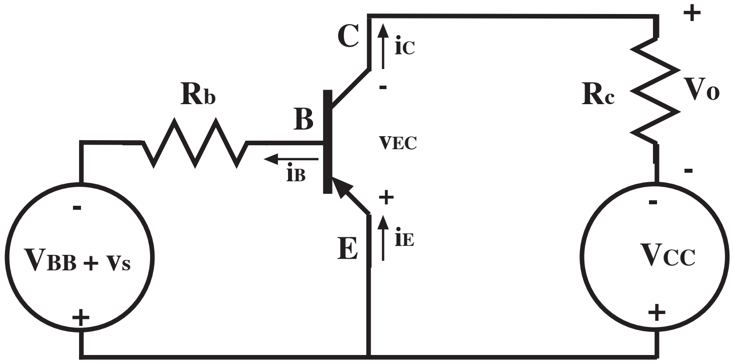
WORKSHEETS
FOR
EXAMINATION 2

Topics Include:
Bipolar Junction Transistor (BJT) Physics
BJT Circuits
Field Effect Transistor (FET) Physics
JFET, Depletion-Mode MOSFET, and Enhancement Mode MOSFET Devices
JFET and MOSFET Circuits

Boltzmann's constant:	$k = 1.381 \times 10^{-23}$ J/K = 8.618×10^{-5} eV/K		
Planck's constant	$h = 4.136 \times 10^{-15}$ eV-sec = 6.626×10^{-34} J-sec		
Electronic charge:	$q = 1.602 \times 10^{-19}$ C		
kT at 300 K	kT = 0.0259 eV	eV-J conversion	1 eV = 1.602×10^{-19} J
Free-space permittivity	$\varepsilon_o = 8.854 \times 10^{-14}$ F/cm	Speed of Light	$c = 2.998 \times 10^{10}$ cm/s
Relative permittivity	Si: 11.9	Ge: 16.0	GaAs: 13.1
Bandgap energies	Si: 1.12 eV	Ge: 0.67 eV	GaAs: 1.42 eV

Common Emitter Circuit Example

Consider a pnp BJT circuit with $\beta = 200$, $R_b = 10.0\ k\Omega$, $V_{BB} = 2.7$ V, $V_{CC} = 16$ V, and $R_c = 200\ \Omega$. Assume the base-emitter turn-on voltage is 0.7 V. Let $v_S = 0$.



Calculate the operating point i_C and v_{EC}.

Kirchhoff's-Voltage-Law on Base Side ($v_{EB} = V_{to}$):

$- V_{BB} + i_B R_b + V_{to} = 0$ or $i_B = (1/R_b)(V_{BB} - V_{to})$

and

$i_C = \beta i_B = (\beta/R_b)(V_{BB} - V_{to})$

$i_C = \beta i_B = (200/10{,}000)(2.7 – 0.7) = 0.040$ A = 40 mA

Kirchhoff's-Voltage-Law on Collector Side (the Load-Line Equation):

$- V_{CC} + i_C R_c + v_{EC} = 0$ or $v_{EC} = V_{CC} - i_C R_c$

$v_{EC} = 16 – (0.040)(200) = 8.0$ V

Check KCL for the transistor.

The currents are:

$i_C = \beta i_B = (200/10{,}000)(2.7 – 0.7) = 0.040$ A = 40 mA

$i_B = (1/10{,}000)(2.7 – 0.7) = 0.00020$ A = 0.20 mA

$i_E = i_C/\alpha_0 = (0.040)/[200/(1 + 200)] = 0.0402$ A = 40.2 mA

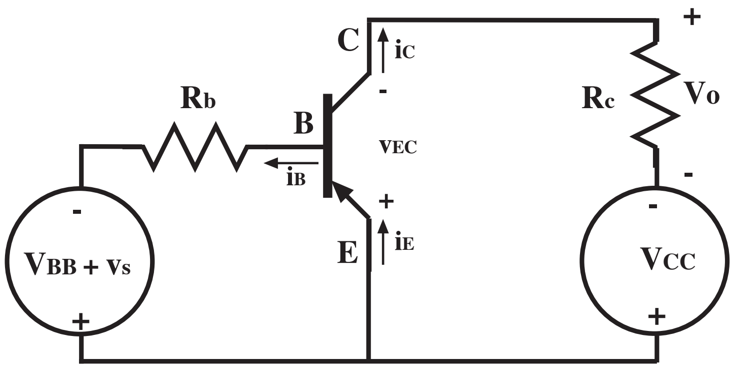
Kirchhoff's Current Law for the transistor gives

$+ i_C + i_B – i_E = 0$

40 mA + 0.2 mA – 40.2 mA = 0

Common Emitter Circuit Example

Consider a pnp BJT circuit with $\beta = 200$, $R_b = 10.0\ k\Omega$, $V_{BB} = 2.7$ V, $V_{CC} = 16$ V, and $R_c = 200\ \Omega$. Assume the base-emitter turn-on voltage is 0.7 V. Let $v_S = 0$.

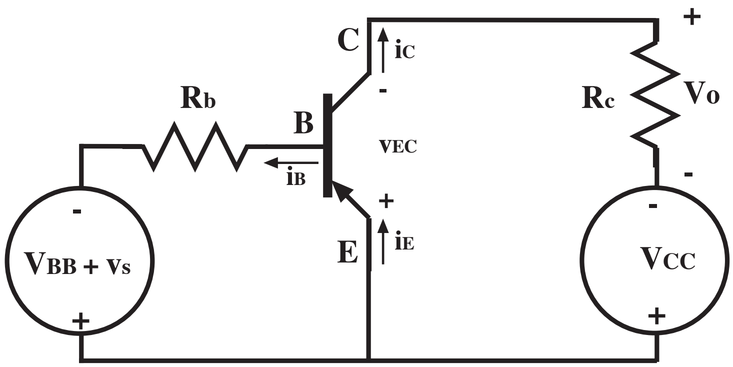


Calculate the operating point i_C and v_{EC}.

Check KCL for the transistor.

Common Emitter Circuit Example

Consider a pnp BJT circuit with $\beta = 200$, $R_b = 10.0\ k\Omega$, $V_{BB} = 4.7$ V, $V_{CC} = 16$ V, and $R_c = 200\ \Omega$. Assume the base-emitter turn-on voltage is 0.7 V and assume that the saturation voltage is $v_{EC,SAT} = 0.2$ V. Let $v_S = 0$.



Calculate the operating point i_C and v_{EC}.

Kirchhoff's-Voltage-Law on Base Side ($v_{EB} = V_{to}$):

$$- V_{BB} + i_B R_b + V_{to} = 0 \quad \text{or} \quad i_B = (1/R_b)(V_{BB} - V_{to})$$

and

$$i_C = \beta i_B = (\beta/R_b)(V_{BB} - V_{to})$$

$$i_C = \beta i_B = (200/10{,}000)(4.7 - 0.7) = 0.080 \text{ A} = 80 \text{ mA}$$

Kirchhoff's-Voltage-Law on Collector Side (the Load-Line Equation):

$$- V_{CC} + i_C R_c + v_{EC} = 0 \quad \text{or} \quad v_{EC} = V_{CC} - i_C R_c$$

$$v_{EC} = 16 - (0.080)(200) = 0 \text{ V} \quad ????????$$

Since $v_{EC} < v_{EC,SAT} = 0.2$ V, the assumption of operation in the active region is invalid, e.g. $i_C \neq \beta i_B$. For operation in the saturation region, use the approximation

$v_{EC} \sim v_{EC,SAT} = 0.2$ V,

Then,

$$- V_{CC} + i_C R_c + v_{EC,SAT} = 0 \quad \text{or} \quad i_C = (1/R_c)(V_{CC} - v_{EC,SAT})$$

$$i_C = (1/200)(16 - 0.2) = 0.079 \text{ A} = 79 \text{ mA}$$

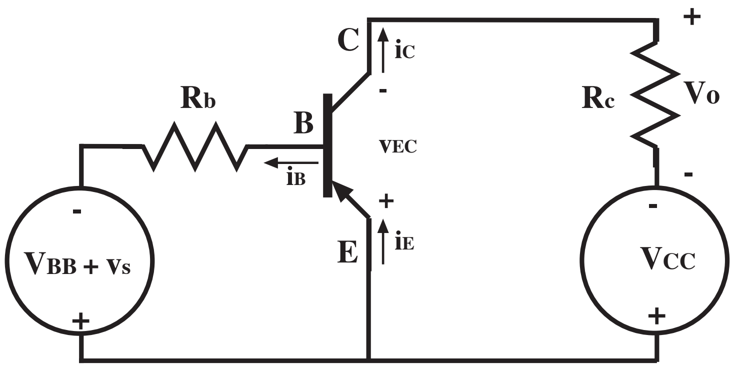
Note that i_B is unchanged with

$$i_B = (1/R_b)(V_{BB} - V_{to}) = (1/10{,}000)(4.7 - 0.7) = 0.00040 \text{ A} = 0.40 \text{ mA}$$

and the effective gain is $\beta_{effective} = i_C/i_B = 79/0.04 = 197.5 \neq \beta = 200$

Common Emitter Circuit Example

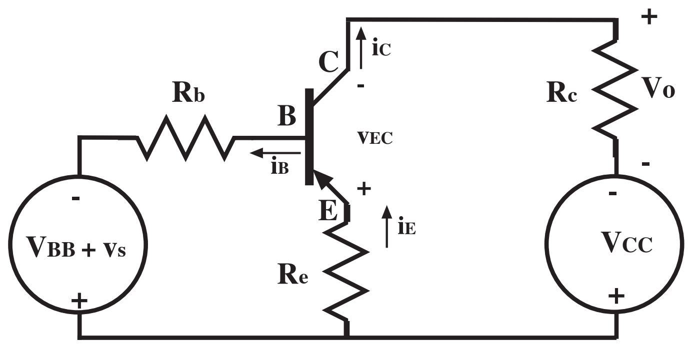
Consider a pnp BJT circuit with $\beta = 200$, $R_b = 10.0\ k\Omega$, $V_{BB} = 4.7$ V, $V_{CC} = 16$ V, and $R_c = 200\ \Omega$. Assume the base-emitter turn-on voltage is 0.7 V and assume that the saturation voltage is $v_{EC,SAT} = 0.2$ V. Let $v_S = 0$.



Calculate the operating point i_C and v_{EC}.

Common Emitter Circuit Example

Consider a pnp BJT circuit with $\beta = 200$, $R_b = 10.0\ k\Omega$, $V_{BB} = 2.7$ V, $V_{CC} = 16$ V, $R_e = 100\ \Omega$, and $R_c = 100\ \Omega$. Assume the base-emitter turn-on voltage is 0.7 V. Let $v_S = 0$.



Calculate the operating point i_C and v_{EC}.

Kirchhoff's-Voltage-Law on Base Side ($v_{EB} = V_{to}$):

$$- V_{BB} + i_B R_b + i_E R_e + V_{to} = 0$$

Since $\beta/\alpha_o = 1 + \beta$ and $i_C = \alpha_o i_E = \beta i_B$, then $i_E = (1 + \beta)i_B$ and

$$i_B = (V_{BB} - V_{to})/[R_e(1 + \beta) + R_b]$$

Also,

$$i_C = \beta i_B = (V_{BB} - V_{to})/[R_e(1 + \beta)/(\beta) + R_b/(\beta)]$$

$$i_C = (2.7 – 0.7)/[100(201/200) + 10{,}000/200] = 0.0133 \text{ A}$$

Kirchhoff's-Voltage-Law on Collector Side (the Load-Line Equation):

$- V_{CC} + i_C R_c + i_E R_e + v_{EC} = 0$ or $v_{EC} = V_{CC} - i_C R_c - i_E R_e$

$v_{EC} = V_{CC} - i_C(R_c + R_e/\alpha_o) = 16 – 0.0133[100 + 100(201)/(200)] = 13.3$ V

Calculate the current i_C if the gain changes to 150.

As before

$$i_C = (2.7 – 0.7)/[100(151/150) + 10{,}000/150] = 0.0120 \text{ A}$$

Note that the current changes by 10%.

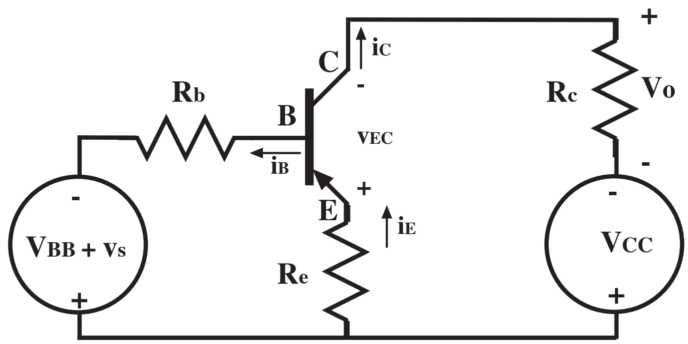
The condition $R_e >> R_b/(\beta)$ was not satisfied.

$R_e = 100\ \Omega$

$R_b/\beta = 10{,}000/200 = 50\ \Omega$

Common Emitter Circuit Example

Consider a pnp BJT circuit with $\beta = 200$, $R_b = 10.0\ k\Omega$, $V_{BB} = 2.7$ V, $V_{CC} = 16$ V, $R_e = 100\ \Omega$, and $R_c = 100\ \Omega$. Assume the base-emitter turn-on voltage is 0.7 V. Let $v_S = 0$.

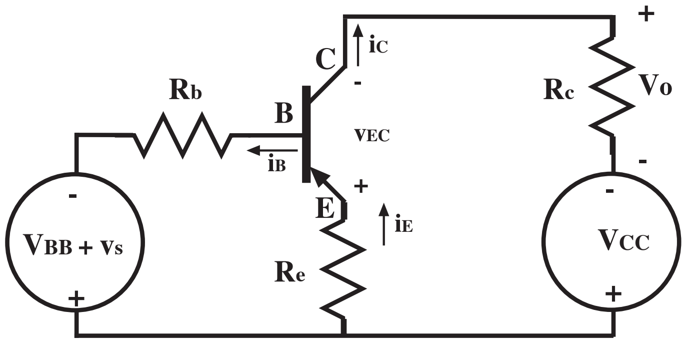


Calculate the operating point i_C and v_{EC}.

Calculate the current i_C if the gain changes to 150.

Common Emitter Circuit Example

Consider a pnp BJT circuit with $\beta = 200$, $R_b = 10.0\ k\Omega$, $V_{BB} = 2.7$ V, $V_{CC} = 16$ V, $R_e =$ **500** Ω, and $R_c =$ **500** Ω. Assume the base-emitter turn-on voltage is 0.7 V. Let $v_S = 0$.



Calculate the operating point i_C and v_{EC}.

Kirchhoff's-Voltage-Law on Base Side ($v_{EB} = V_{to}$):

$$- V_{BB} + i_B R_b + i_E R_e + V_{to} = 0$$

Since $\beta/\alpha_o = 1 + \beta$ and $i_C = \alpha_o i_E = \beta i_B$, then $i_E = (1 + \beta) i_B$ and

$$i_B = (V_{BB} - V_{to})/[R_e(1 + \beta) + R_b] \text{ or}$$

Also,

$$i_C = \beta i_B = (V_{BB} - V_{to})/[R_e(1 + \beta)/(\beta) + R_b/(\beta)]$$

$$i_C = (2.7 - 0.7)/[500(201/200) + 10{,}000/200] = 0.00362 \text{ A}$$

Kirchhoff's-Voltage-Law on Collector Side (the Load-Line Equation):

$- V_{CC} + i_C R_c + i_E R_e + v_{EC} = 0$ or $v_{EC} = V_{CC} - i_C R_c - i_E R_e$

$v_{EC} = V_{CC} - i_C(R_c + R_e/\alpha_o) = 16 - 0.00362[500 + 500(201)/(200)] = 12.4$ V

Calculate the current i_C if the gain changes to 150.

As before

$$i_C = (2.7 - 0.7)/[500(151/150) + 10{,}000/150] = 0.00351 \text{ A}$$

Note that the current changes by about 3%.

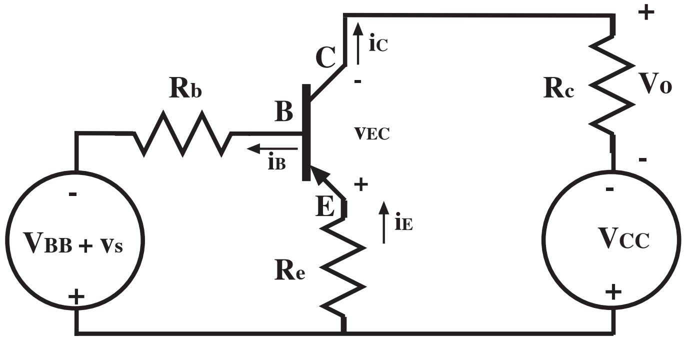
Note the condition $R_e > R_b/(\beta)$ by a factor of ten.

$R_e = 500\ \Omega$

$R_b/\beta = 10{,}000/200 = 50\ \Omega$

Common Emitter Circuit Example

Consider a pnp BJT circuit with $\beta = 200$, $R_b = 10.0\ k\Omega$, $V_{BB} = 2.7$ V, $V_{CC} = 16$ V, $R_e =$ **500** Ω, and $R_c =$ **500** Ω. Assume the base-emitter turn-on voltage is 0.7 V. Let $v_S = 0$.

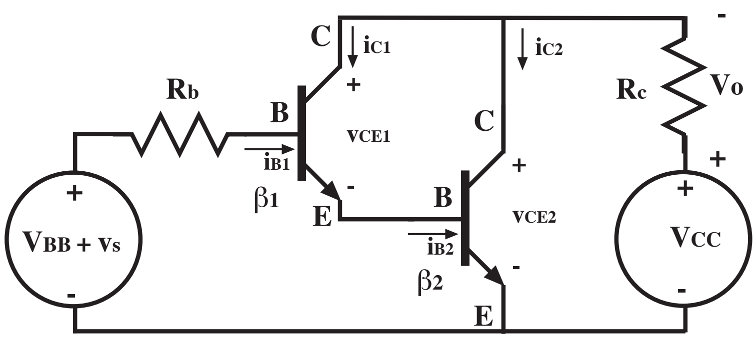


Calculate the operating point i_C and v_{EC}.

Calculate the current i_C if the gain changes to 150.

Darlington Amplifier Circuit Example

Consider an npn BJT circuit with $\beta = 50$, $R_b = 100.0\ k\Omega$, $V_{BB} = 3.4$ V, $V_{CC} = 16$ V, and $R_c = 200\ \Omega$. Assume the base-emitter turn-on voltage is 0.7 V. Let $v_S = 0$.



Calculate the currents i_{C1} and i_{C2}.

Kirchhoff's-Voltage-Law on Base Side ($v_{BE1} = v_{BE2} = V_{to}$):

$- V_{BB} + i_{B1} R_b + 2V_{to} = 0$ or $i_{B1} = (1/R_b)(V_{BB} - 2V_{to})$

and

$i_{C1} = \beta i_{B1} = (\beta/R_b)(V_{BB} - 2V_{to})$

$i_{C1} = \beta i_{B1} = (50/100{,}000)(3.4 – 1.4) = 0.001$ A $= 1.0$ mA

$i_{C2} = \beta_2 i_{B2} = \beta_2 i_{E1} = \beta_2 i_{C1}/\alpha_{o1} = \beta_2\beta_1 i_{B1}/\alpha_{o1} = \beta_2(1 + \beta_1)i_{B1}$

$i_{C2} = \beta(1 + \beta)(1/R_b)(V_{BB} - 2V_{to})$

$i_{C2} = 50(1 + 50)(1/100{,}000)(3.4 – 1.4) = 0.051$ A $= 51$ mA

$i_{CTotal} = i_{C1} + i_{C2} = 52$ mA

Calculate the voltages v_{CE1} and v_{CE2}.

Kirchhoff's-Voltage-Law on Collector Side (the Load-Line Equation):

$- V_{CC} + i_{CTotal} R_c + v_{CE1} + V_{to} = 0$ or $v_{CE1} = V_{CC} - V_{to} - i_{CTotal}R_c$

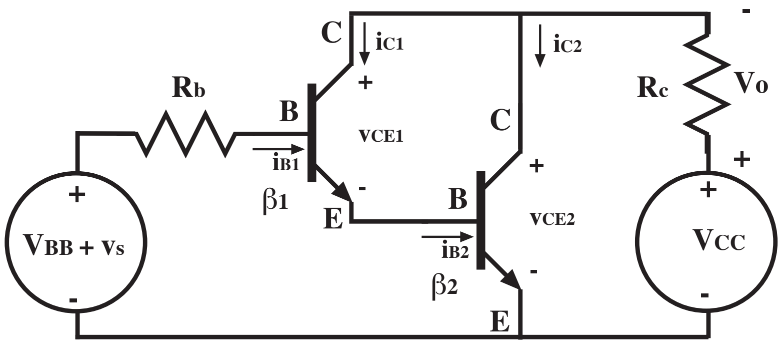
$v_{CE1} = V_{CC} - V_{to} - i_{CTotal}R_c = 16 – 0.7 – 0.052(200) = 4.9$ V

$- V_{CC} + i_{CTotal} R_c + v_{CE2} = 0$ or $v_{CE2} = V_{CC} - i_{CTotal}R_c$

$v_{CE2} = V_{CC} - i_{CTotal}R_c = 16 – 0.052(200) = 5.6$ V

Darlington Amplifier Circuit Example

Consider an npn BJT circuit with $\beta = 50$, $R_b = 100.0\ k\Omega$, $V_{BB} = 3.4$ V, $V_{CC} = 16$ V, and $R_c = 200\ \Omega$. Assume the base-emitter turn-on voltage is 0.7 V. Let $v_S = 0$.

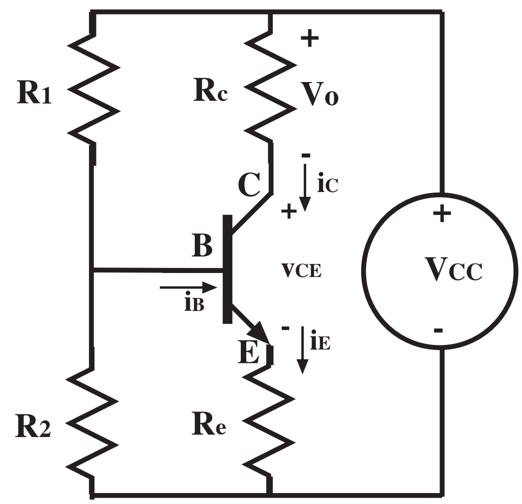


Calculate the currents i_{C1} and i_{C2}.

Calculate the voltages v_{CE1} and v_{CE2}.

Common Emitter Circuit Example

Consider an npn BJT circuit with $\beta = 200$, $R_1 = 40.0\ k\Omega$, $R_2 = 10.0\ k\Omega$, $V_{CC} = 15\ V$, $R_e = 1.0\ k\Omega$, and $R_c = 1.0\ k\Omega$. Assume the base-emitter turn-on voltage is 0.7 V.



Calculate the Thevenin equivalent with respect to the Base circuit, i.e. V_{BB} and R_b.

$V_{BB} = V_{TH} = V_{CC}\,[R_2/(R_1 + R_2)] = 15\ V\,[10{,}000/(10{,}000 + 40{,}000)]$
$V_{BB} = 3.0\ V$

$R_b = R_{TH} = R_1 || R_2 = [R_1R_2/(R_1 + R_2)] = [(10{,}000)(40{,}000)/(10{,}000 + 40{,}000)]$
$R_b = 8{,}000\ \Omega$

Calculate the operating point i_C and v_{CE}.

Kirchhoff's-Voltage-Law on Base Side ($v_{BE} = V_{to}$):

$- V_{BB} + i_B R_b + i_E R_e + V_{to} = 0$

Since $\beta/\alpha_o = 1 + \beta$ and $i_C = \alpha_o i_E = \beta i_B$, then $i_E = (1 + \beta) i_B$ and

$i_B = (V_{BB} - V_{to})/[R_e(1 + \beta) + R_b]$

$i_C = \beta i_B = (V_{BB} - V_{to})/[R_e(1 + \beta)/(\beta) + R_b/(\beta)]$

$i_C = (3.0 – 0.7)/[1000(201/200) + 8{,}000/200] = 0.00220\ A$

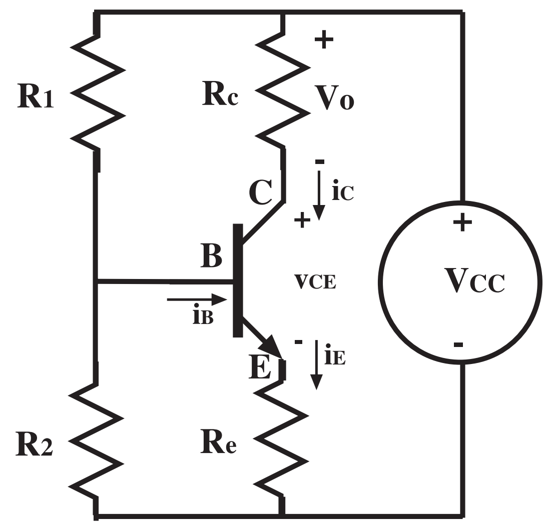
Kirchhoff's-Voltage-Law on Collector Side (the Load-Line Equation):

$- V_{CC} + i_C R_c + i_E R_e + v_{CE} = 0$ or $v_{CE} = V_{CC} - i_C R_c - i_E R_e$

$v_{CE} = V_{CC} - i_C(R_c + R_e/\alpha_o) = 15 – 0.00220[1000 + 1000(201)/(200)] = 10.6\ V$

Common Emitter Circuit Example

Consider an npn BJT circuit with $\beta = 200$, $R_1 = 40.0\ k\Omega$, $R_2 = 10.0\ k\Omega$, $V_{CC} = 15$ V, $R_e = 1.0\ k\Omega$, and $R_c = 1.0\ k\Omega$. Assume the base-emitter turn-on voltage is 0.7 V.

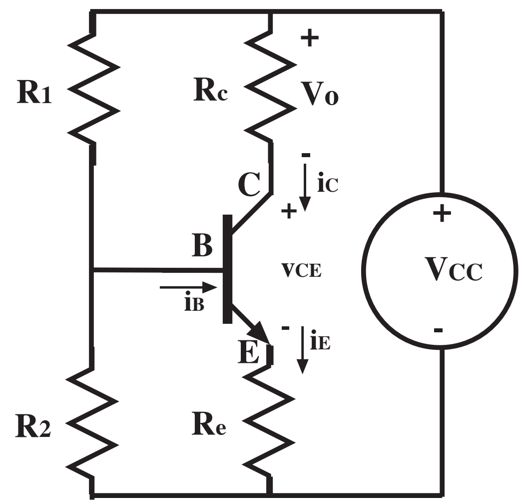


Calculate the Thevenin equivalent with respect to the Base circuit, i.e. V_{BB} *and* R_b.

Calculate the operating point i_C *and* v_{CE}.

Common Emitter Circuit Example

Consider an npn BJT circuit with $\beta = 200$, $R_b = 10.0$ kΩ, $V_{BB} = 2.7$ V, $V_{CC} = 16$ V, $R_e = 500$ Ω, and $R_c = 500$ Ω. Assume the base-emitter turn-on voltage is 0.7 V.



Calculate the value of resistors R_1 and R_2 that will produce the equivalent circuit for $R_b = 10.0\ k\Omega$ and $V_{BB} = 2.7\ V$.

The Thevenin equivalent for the circuit to the left of the Base terminal

$V_{BB} = V_{TH} = V_{CC}\,[R_2/(R_1 + R_2)]$ $\qquad$ $R_b = R_{TH} = R_1||R_2 = [R_1R_2/(R_1 + R_2)]$

Hence,
$V_{BB} = V_{CC}[R_2/(R_1 + R_2)] = V_{CC}[1/R_1][R_1R_2/(R_1 + R_2)] = V_{CC}[1/R_1]\,R_b$
Similarly,
$V_{CC} - V_{BB} = V_{CC}[R_1/(R_1 + R_2)] = V_{CC}[1/R_2][R_1R_2/(R_1 + R_2)] = V_{CC}[1/R_2]\,R_b$

Then,
$R_1 = (V_{CC}/V_{BB})\,R_b = (16\text{ V}/2.7\text{ V})\ 10.0\text{ k}\Omega = 59.26\text{ k}\Omega$
$R_2 = [V_{CC}/(V_{CC} - V_{BB})]\,R_b = [16\text{ V}/(16 - 2.7\text{ V})]\ 10.0\text{ k}\Omega = 12.03\text{ k}\Omega$

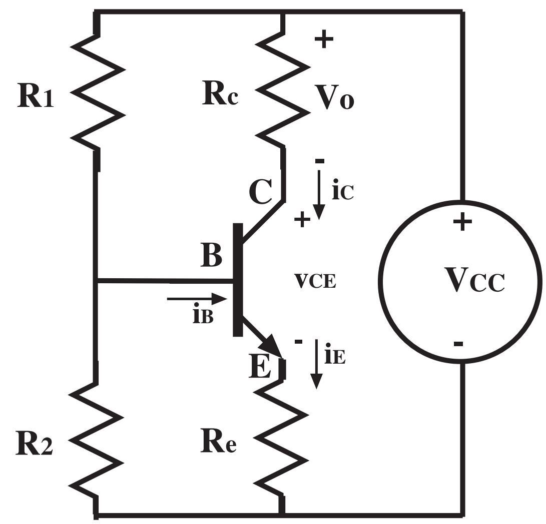
Calculate the operating point i_C and v_{CE}.

Kirchhoff's-Voltage-Law on Base Side ($v_{BE} = V_{to}$):
$- V_{BB} + i_B R_b + i_E R_e + V_{to} = 0$
Since $\beta/\alpha_o = 1 + \beta$ and $i_C = \alpha_o i_E = \beta i_B$, then $i_E = (1 + \beta)i_B$ and
$i_B = (V_{BB} - V_{to})/[R_e(1 + \beta) + R_b]$
$i_C = \beta i_B = (V_{BB} - V_{to})/[R_e(1 + \beta)/(\beta) + R_b/(\beta)]$
$i_C = (2.7 - 0.7)/[500(201/200) + 10{,}000/200] = 0.00362\text{ A}$

Kirchhoff's-Voltage-Law on Collector Side (the Load-Line Equation):
$- V_{CC} + i_C R_c + i_E R_e + v_{CE} = 0$ or $v_{CE} = V_{CC} - i_C R_c - i_E R_e$
$v_{CE} = V_{CC} - i_C(R_c + R_e/\alpha_o) = 16 - 0.00362[500 + 500(201)/(200)] = 12.4\text{ V}$

Common Emitter Circuit Example

Consider an npn BJT circuit with $\beta = 200$, $R_b = 10.0\ k\Omega$, $V_{BB} = 2.7$ V, $V_{CC} = 16$ V, $R_e = 500\ \Omega$, and $R_c = 500\ \Omega$. Assume the base-emitter turn-on voltage is 0.7 V.

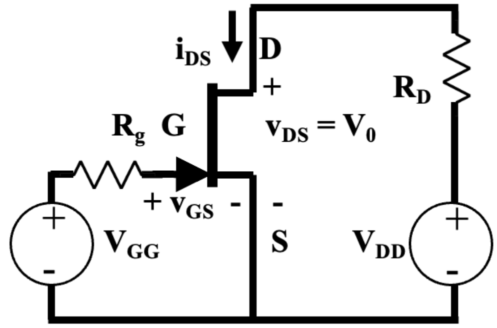


Calculate the value of resistors R_1 and R_2 that will produce the equivalent circuit for $R_b = 10.0\ k\Omega$ and $V_{BB} = 2.7$ V.

Calculate the operating point i_C and v_{CE}.

Common Source JFET Circuit Example

Consider a n-channel JFET circuit with V_{po} = 5.0 V, I_{DSS} = 1.0 mA, R_d = ?? Ω, v_{GS} = V_{GG} = V_i (since i_G = 0), and V_{DD} = 15 V.



Calculate the maximum input voltage V_i for which the JFET operating point has i_{DS} = 0 A. Also, calculate v_{DS}.

Since $V_{GG} = v_{GS}$, the maximum input voltage or maximum v_{GS} for $i_{DS} = 0$ occurs at $v_{GS} = -V_{po} = -5.0$ V as seen in equation $i_{DS} = I_{DSS}(1 + v_{GS}/V_{po})^2$. The load line gives $v_{DS} = V_{DD} - i_{DS}R_d$ = 15 V – 0 = 15 V.

Hence, the input voltage $V_{GG} = V_i$ = -5.0 V
gives an operating point of v_{DS} = 15 V and i_{DS} = 0 A.

Calculate the input voltage V_i for which the JFET operating point has $i_{DS} = I_{DSS}$ and the JFET is just in saturation. Also, calculate v_{DS}.

Note that $i_{DS} = I_{DSS}$ only for saturation with the input voltage v_{GS} = 0. Saturation just occurs for $v_{DS} = V_{po}$ = 5 V.

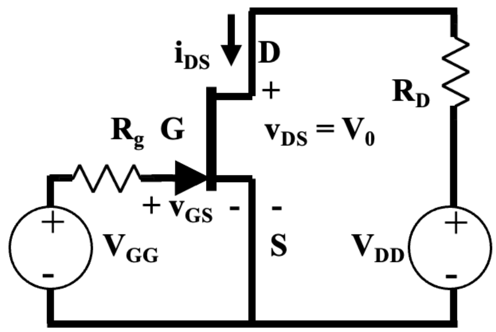
Hence, the input voltage $V_{GG} = V_i$ = 0 V
gives an operating point of v_{DS} = 5 V and i_{DS} = 1 mA.

Calculate the resistance R_d for which the JFET circuit load line passes through both of these operating points.

The load line is $v_{DS} = V_{DD} - i_{DS}R_d$. One intercept corresponds to the first operating point v_{DS} = 15 V and i_{DS} = 0 A. The second operating point v_{DS} = 5 V and i_{DS} = 1 mA requires
$R_d = (V_{DD} - v_{DS})/i_{DS}$ = (15 – 5)/0.001 = 10 kΩ.

Common Source JFET Circuit Example

Consider a n-channel JFET circuit with V_{po} = 5.0 V, I_{DSS} = 1.0 mA, R_d = ?? Ω, v_{GS} = V_{GG} = V_i (since i_G = 0), and V_{DD} = 15 V.



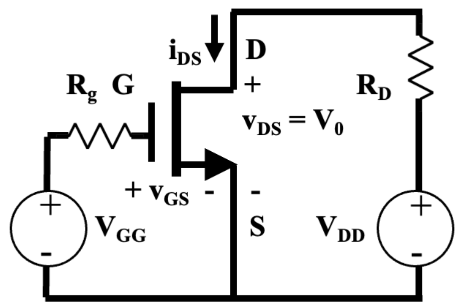
Calculate the maximum input voltage V_i for which the JFET operating point has i_{DS} = 0 A. Also, calculate v_{DS}.

Calculate the input voltage V_i for which the JFET operating point has $i_{DS} = I_{DSS}$ and the JFET is just in saturation. Also, calculate v_{DS}.

Calculate the resistance R_d for which the JFET circuit load line passes through both of these operating points.

Common Source MOSFET Circuit Examples

Consider a n-channel depletion-mode MOSFET circuit with V_{po} = 5.0 V, I_{DSS} = 1.0 mA, $v_{GS} = V_{GG} = V_i$ ($i_G = 0$), and V_{DD} = 15 V.



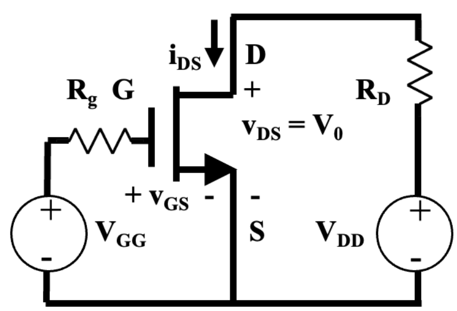
Calculate the input voltage V_i for which the MOSFET circuit load line has i_{DS} = 0 A, i_{DS} =1 mA, and i_{DS} = 2 mA for saturation.

Note that for saturation $i_{DS} = I_{DSS}(1 + v_{GS}/V_{po})^2$.
Hence, for i_{DS} = 0 A, $V_i = v_{GS} = - V_{po}$ = - 5.0 V
Hence for i_{DS} = 1 mA for $V_{GG} = V_i = v_{GS}$ = 0 V
Hence, for i_{DS} = 2 mA, $V_{GG} = V_i = v_{GS} = + V_{po} (\sqrt{2} - 1)$ = + 2.07 V

Calculate the resistance R_d for which the MOSFET circuit load line passes through operating points (v_{DS} = 15 V, i_{DS} = 0 A) and (v_{DS} = 5 V, i_{DS} = 1 mA).

The load line is $v_{DS} = V_{DD} - i_{DS}R_d$. One intercept is ($v_{DS}$ = 15 V, i_{DS} = 0 A).
The second operating point v_{DS} = 5 V and i_{DS} = 1 mA requires
$R_d = (V_{DD} - v_{DS})/i_{DS} = (15 - 5)/0.001 = 10$ kΩ.

Consider a n-channel enhancement-mode MOSFET circuit with V_{on} = 2.0 V, K = 0.04 mA/V^2, $v_{GS} = V_{GG} = V_i$ ($i_G = 0$), and V_{DD} = 15 V.



Calculate the input voltage V_i for which the MOSFET circuit load line has i_{DS} = 0 A, i_{DS} = 1 mA, and i_{DS} = 2 mA for saturation.

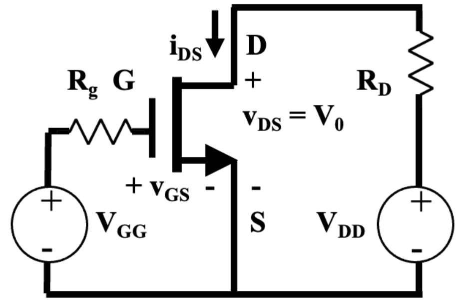
Note that for saturation $i_{DS} = KV_{on}^2(v_{GS}/V_{on} - 1)^2$.
Hence, for i_{DS} = 0 A, $V_i = v_{GS} = V_{on}$ = 2.0 V
Hence for i_{DS} = 1 mA for $V_{GG} = V_i = v_{GS}$ = 07.0 V
Hence, for i_{DS} = 2 mA, $V_{GG} = V_i = v_{GS} = + V_{on}$ (4.54) = + 9.07 V

Calculate the resistance R_d for which the MOSFET circuit load line passes through operating points (v_{DS} = 15 V, i_{DS} = 0 A) and (v_{DS} = 5 V, i_{DS} = 1 mA).

The load line is the same, i.e. $v_{DS} = V_{DD} - i_{DS}R_d$. Then
$R_d = (V_{DD} - v_{DS})/i_{DS} = (15 - 5)/0.001 = 10$ kΩ.

Common Source MOSFET Circuit Examples

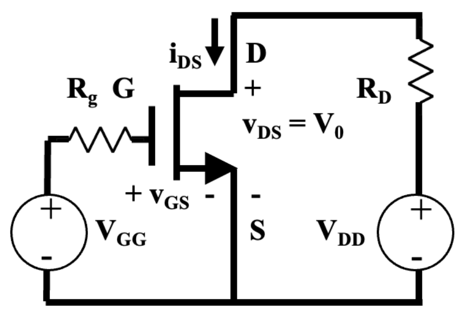
Consider a n-channel depletion-mode MOSFET circuit with $V_{po} = 5.0$ V, $I_{DSS} = 1.0$ mA, $v_{GS} = V_{GG} = V_i$ ($i_G = 0$), and $V_{DD} = 15$ V



Calculate the input voltage V_i for which the MOSFET circuit load line has $i_{DS} = 0$ A, $i_{DS} = 1$ mA, and $i_{DS} = 2$ mA for saturation.

Calculate the resistance R_d for which the MOSFET circuit load line passes through operating points ($v_{DS} = 15$ V, $i_{DS} = 0$ A) and ($v_{DS} = 5$ V, $i_{DS} = 1$ mA).

Consider a n-channel enhancement-mode MOSFET circuit with $V_{on} = 2.0$ V, $K = 0.04$ mA/V^2, $v_{GS} = V_{GG} = V_i$ ($i_G = 0$), and $V_{DD} = 15$ V.



Calculate the input voltage V_i for which the MOSFET circuit load line has $i_{DS} = 0$ A, $i_{DS} = 1$ mA, and $i_{DS} = 2$ mA for saturation.

Calculate the resistance R_d for which the MOSFET circuit load line passes through operating points ($v_{DS} = 15$ V, $i_{DS} = 0$ A) and ($v_{DS} = 5$ V, $i_{DS} = 1$ mA).

MOSFET Current Example

An enhancement-mode MOSFET (n-channel) has

V_{on} = 0.50 V and
K = 0.20 mA/V^2,

Saturation Conditions

$$v_{DS} - v_{GS} \geq -V_{on}$$

MOSFET Relationships

$$i_{DS} = KV_{on}^2\left[2\left(\frac{v_{GS}}{V_{on}} - 1\right)\left(\frac{v_{DS}}{V_{on}}\right) - \left(\frac{v_{DS}}{V_{on}}\right)^2\right]$$

$$i_{DS} = KV_{on}^2\left(\frac{v_{GS}}{V_{on}} - 1\right)^2$$

Calculate the drain-source current i_{DS} if v_{DS} = +5.0 V and v_{GS} = 0 V

Since $v_{GS} = 0 < V_{on}$ = 0.50 V, the current is zero.

Then, $i_{DS} = 0$

Calculate the drain-source current i_{DS} if v_{DS} = +5.0 V and v_{GS} = + 3.0 V

Since $v_{DS} - v_{GS} = 5 - 3 = 2\ V \geq -V_{on} = -0.5$ V (inequality satisfied), the MOSFET has saturated operation.

Then, $i_{DS} = K\ V_{on}^2\ [(v_{GS}/V_{on}) - 1]^2 = (0.20)\ (0.50)^2\ [(3.0/0.5) - 1]^2 = 1.25$ mA

Calculate the drain-source current i_{DS} if v_{DS} = +5.0 V and v_{GS} = + 6.0 V

Since $v_{DS} - v_{GS} = 5 - 6 = -1\ V < -V_{on} = -0.5$ V, (inequality not satisfied) the MOSFET has unsaturated operation.

Then, $i_{DS} = K\ V_{on}^2\ \{2[(v_{GS}/V_{on}) - 1](v_{DS}/V_{on}) - (v_{DS}/V_{on})^2\}$
$i_{DS} = (0.20)\ (0.50)^2\ \{2[(6.0/0.5) - 1]\ (5.0/0.5) - (5.0/0.5)^2\} = 6.0$ mA

MOSFET Current Example

An enhancement-mode MOSFET (n-channel) has

$V_{on} = 0.50$ V and
$K = 0.20$ mA/V^2,

Saturation Conditions

$$v_{DS} - v_{GS} \geq -V_{on}$$

MOSFET Relationships

$$i_{DS} = KV_{on}{}^2\left[2\left(\frac{v_{GS}}{V_{on}} - 1\right)\left(\frac{v_{DS}}{V_{on}}\right) - \left(\frac{v_{DS}}{V_{on}}\right)^2\right]$$

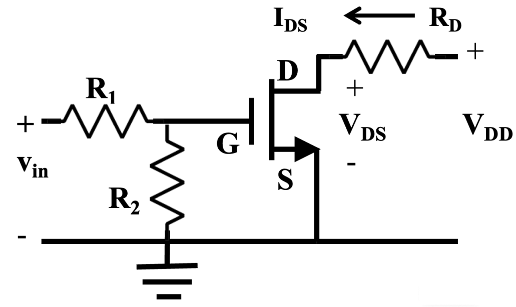
$$i_{DS} = KV_{on}{}^2\left(\frac{v_{GS}}{V_{on}} - 1\right)^2$$

Calculate the drain-source current i_{DS} if $v_{DS} = +5.0$ V and $v_{GS} = 0$ V

Calculate the drain-source current i_{DS} if $v_{DS} = +5.0$ V and $v_{GS} = +3.0$ V

Calculate the drain-source current i_{DS} if $v_{DS} = +5.0$ V and $v_{GS} = +6.0$ V

Enhancement-mode MOSFET Circuit



Consider an n-channel enhancement-mode MOSFET circuit with $V_{on} = 2.0$ V, $K = 0.25$ mA/V^2, $R_D = 1.5$ kΩ, $R_1 = 4.0$ kΩ, $R_2 = 6.0$ kΩ, and $V_{DD} = 10$ V.

Calculate the operating point for an input voltage $v_{in} = 0$ V.

Note that $i_G = 0$. Then, R_1 and R_2 form a voltage divider.
$v_{GS} = v_{in} [R_2 /(R_1 + R_2)] = 0$ V
Since $v_{GS} = 0 \text{ V} < V_{on} = 2.0$ V, the current $i_{DS} = 0$ A.
The load line is $v_{DS} = V_{DD} - i_{DS}R_d = 10 \text{ V} - 0 = 10$ V.
The operating point is
$v_{DS} = 10$ V and $i_{DS} = 0$ A.

Note that a low input produces a high output.

Calculate the operating point for an input voltage $v_{in} = 10$ V.

Note that $i_G = 0$. Then, R_1 and R_2 form a voltage divider.
$v_{GS} = v_{in} [R_2 /(R_1 + R_2)] = 10 [6 / (4 + 6)] = 6.0$ V
Assuming saturation, $i_{DS} = KV_{on}^2(v_{GS}/V_{on} - 1)^2 = (0.25 \text{ mA})(2)^2$ (
$i_{DS} = (0.25 \text{ mA}) (2)^2 [(6/2) - 1]^2 = 4.0$ mA

The load line is $v_{DS} = V_{DD} - i_{DS}R_d = 10 \text{ V} - (0.004)(1500) = 4.0$ V.
Note that the inequality for saturation is satisfied
$v_{DS} - v_{GS} = 4 - 6 = -2 \text{ V} \geq - V_{on} = - 2$ V

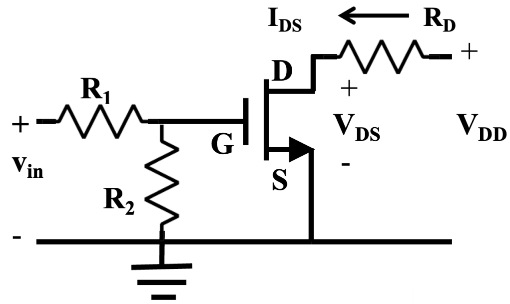
The operating point is
$v_{DS} = 4.0$ V and $i_{DS} = 4.0$ mA.

A different approach is to calculate the Thevenin circuit for the input.
Then, $V_{GG} = v_{Th} = v_{in} [R_2 /(R_1 + R_2)] = 6.0$ V.
Also, $R_{Th} = (R_1 R_2)/(R_1 + R_2) = R_g$. (This does not matter since $i_G = 0$.)

Note that a high input produces a low output.

Enhancement-mode MOSFET Circuit

Consider an n-channel enhancement-mode MOSFET circuit with V_{on} = 2.0 V, K = 0.25 mA/V^2, R_D =1.5 kΩ, R_1 = 4.0 kΩ, R_2 = 6.0 kΩ, and V_{DD} = 10 V.

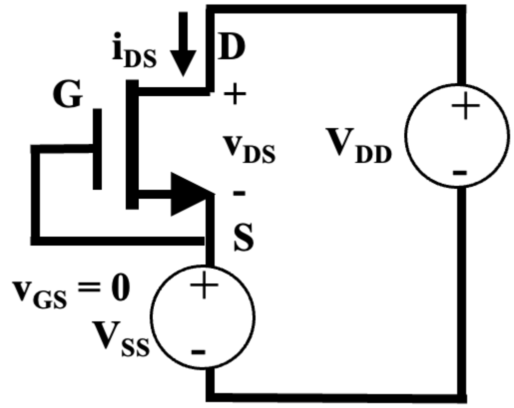


Calculate the operating point for an input voltage v_{in} = 0 V.

Calculate the operating point for an input voltage v_{in} = 10 V.

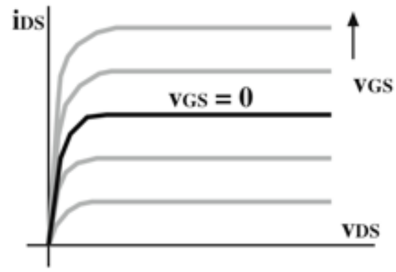
MOSFET Circuit as an Active Load

Consider a n-channel depletion-mode MOSFET circuit with $V_{po} = 5.0$ V and $I_{DSS} = 1.0$ mA. (Note that $v_{GS} = 0$ V.) and $v_{DS} = V_{DD} - V_{SS}$



Calculate the current i_{DS} for which the MOSFET circuit has
$v_{DS} = V_{DD} - V_{SS} = 0.5\ V_{po}$.

Since $v_{DS} = 0.5\ V_{po} < V_{po}$, the transistor is not saturated and
$i_{DS} = I_{DSS}[2(1 + v_{GS}/V_{po})(v_{DS}/V_{po}) – (v_{DS}/V_{po})^2]$ for $v_{GS} = 0$ V.
Then,
$i_{DS} = I_{DSS}[2(1 + 0\ )(v_{DS}/V_{po}) – (v_{DS}/V_{po})^2]$
$i_{DS} = (1.0\text{ mA})[2(1)(0.5) – (0.5)^2] = 0.75$ mA



Calculate the current i_{DS} for which the MOSFET circuit has $v_{DS} = V_{DD} - V_{SS} = V_{po}$.

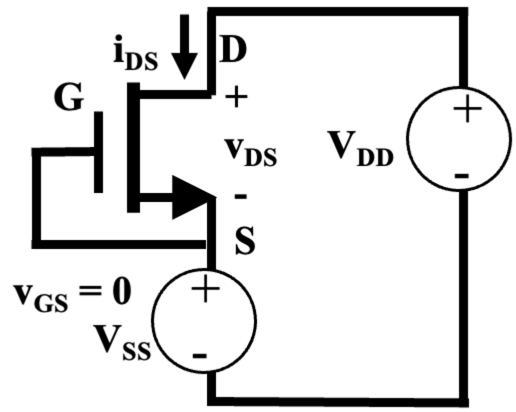
Since $v_{DS} = V_{po}$, the transistor is at the threshold of saturation.
Both equations apply.
Using $i_{DS} = I_{DSS}[2(1 + v_{GS}/V_{po})(v_{DS}/V_{po}) – (v_{DS}/V_{po})^2]$ for $v_{GS} = 0$ V.
Then, $i_{DS} = I_{DSS}[2(v_{DS}/V_{po}) – (v_{DS}/V_{po})^2] = (1.0\text{ mA})[2(1) – (1)^2] = 1.0$ mA
Using $i_{DS} = I_{DSS}(1 + v_{GS}/V_{po})^2$ for $v_{GS} = 0$ V.
Then, $i_{DS} = I_{DSS}(1 + 0) = 1.0$ mA

Calculate the current i_{DS} for which the MOSFET circuit has
$v_{DS} = V_{DD} - V_{SS} = 2\ V_{po}$.

Since $v_{DS} = 2\ V_{po} > V_{po}$, the transistor is in saturation and
$i_{DS} = I_{DSS}$ for $v_{GS} = 0$ V.
Then,
$i_{DS} = 1.0$ mA

MOSFET Circuit as an Active Load

Consider a n-channel depletion-mode MOSFET circuit with $V_{po} = 5.0$ V and $I_{DSS} = 1.0$ mA. (Note that $v_{GS} = 0$ V.) and $v_{DS} = V_{DD} - V_{SS}$



Calculate the current i_{DS} for which the MOSFET circuit has

$$v_{DS} = V_{DD} - V_{SS} = 0.5\ V_{po} .$$

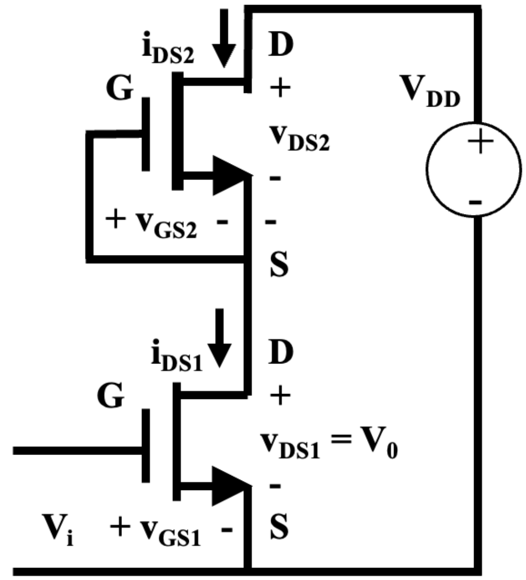
Calculate the current i_{DS} for which the MOSFET circuit has $v_{DS} = V_{DD} - V_{SS} = V_{po}$.

Calculate the current i_{DS} for which the MOSFET circuit has

$$v_{DS} = V_{DD} - V_{SS} = 2\ V_{po} .$$

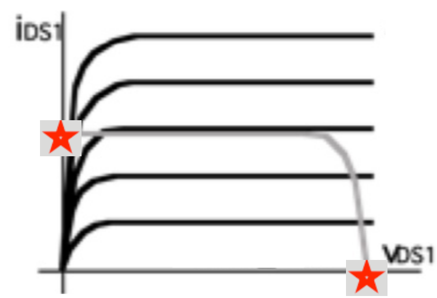
MOSFET Inverter Circuit with an Active Load

Consider the inverter circuit shown with supply voltage V_{DD} = 5.00 V. The enhancement-mode MOSFET has
V_{on} = 0.50 V and K = 1.00 mA/V^2
and the depletion-mode MOSFET has
V_{po} = 2.00 V and I_{DSS} = 1.50 mA.



Sketch the load-line (LL) on the i_{DS} for v_{DS1} family of curves and calculate the load-line intercepts.

LL KVL is $- V_{DD} + v_{DS2} + v_{DS1} = 0$
When $i_{DS} = 0$, the depletion-mode MOSFET
has $v_{DS2} = 0$. Then the LL gives v_{DS1} as
$v_{DS1} = V_{DD} - v_{DS2} = V_{DD} - 0 = V_{DD} =$ 5.00 V
LL Voltage-axis intercept:
(V_{DD}, 0 mA) or (5.00 V, 0 mA)
When $v_{DS1} = 0$, the maximum current for the active load is $i_{DS} = I_{DSS}$ = 1.5 mA.
Note that $i_{DS} = i_{DS1} = i_{DS2}$. Then,
LL Current-axis intercept:
(0 V, I_{DSS}) or (0, 1.50 mA)



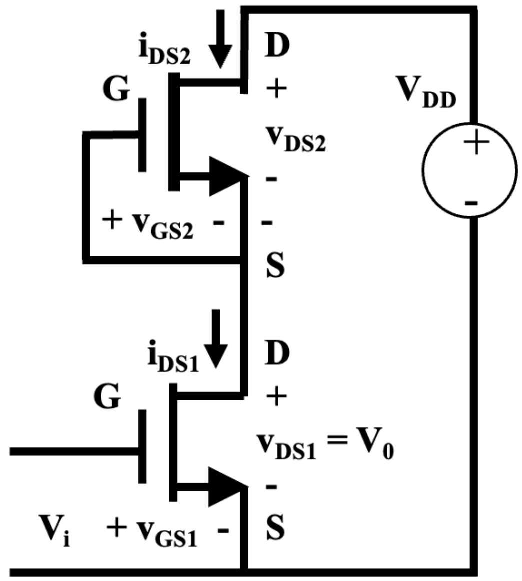
Determine the region of operation (saturated or unsaturated) for the enhancement-mode MOSFET for V_i = 0 V and V_i = 4.00 V.

If $V_i = v_{GS1} = 0 \text{ V} < V_{ON}$, then $i_{DS} = i_{DS1} = i_{DS2} = 0$. The operating point is the voltage-axis LL intercept.
Saturated Operation
If $V_i = v_{GS1} = 4.00$ V ($V_i > V_{ON}$), then saturated operating conditions are checked.
$i_{DS1} = KV_{on}^2(-1 + v_{GS1}/V_{on})^2 = 1.75 \text{ mA} > 1.5 \text{ mA} = I_{DSS} = i_{DS1MAX}$. Not possible!
(The operating point is near the current-axis LL intercept.)
Hence, I_{DSS} = 1.50 mA and v_{DS1} is the solution of
$i_{DS1} = KV_{on}^2 \,[2(-1 + v_{GS1}/V_{on})(v_{DS1}/V_{on}) - (v_{DS1}/V_{on})^2]$ for
Unsaturated Operation

The solution of $1.5 \text{ mA} = (1)(0.5)^2 \,[2(-1 + 4/0.5)(v_{DS1}/0.5) - (v_{DS1}/0.5)^2]$ is
v_{DS1} = 0.2213 V. Note that $v_{DS1} - v_{GS1} = -3.778 < -V_{ON} = -0.5$ V; the inequality is not satisfied for saturated operation.

MOSFET Inverter Circuit with an Active Load

Consider the inverter circuit shown with supply voltage V_{DD} = 5.00 V. The enhancement-mode MOSFET has
V_{on} = 0.50 V and K = 1.00 mA/V^2
and the depletion-mode MOSFET has
V_{po} = 2.00 V and I_{DSS} = 1.50 mA.

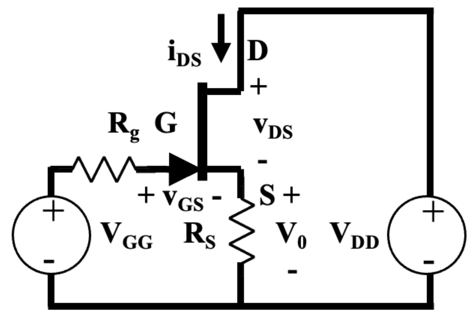


Sketch the load-line (LL) on the i_{DS} for v_{DS1} family of curves and calculate the load-line intercepts.

Determine the region of operation (saturated or unsaturated) for the enhancement-mode MOSFET for V_i = 0 V and V_i = 4.00 V.

Source Follower JFET Circuit Example

Consider a n-channel JFET circuit with
$V_{po} = 5.0$ V, $I_{DSS} = 1.0$ mA, $R_s = 1000\ \Omega$,
$V_{GG} = -2.5$ V, and $V_{DD} = 15$ V.
(Note that $v_{GS} \neq V_{GG}$.)



Calculate the operating point v_{DS} and i_{DS}.

Analysis for Operating Point (v_{DS}, i_{DS}).

Kirchhoff's-Voltage-Law on Gate-Source Side:

$$-V_{GG} + i_{DS} R_s + v_{GS} = 0 \quad \text{or} \quad v_{GS} = V_{GG} - i_{DS}R_s$$

and for operation in the saturation region

$$-V_{po} < v_{GS} = (V_{GG} - i_{DS}R_s) < 0 \text{ and } i_{DS} = I_{DSS}(1 + v_{GS}/V_{po})^2.$$

The simultaneous solution is

$$i_{DS} = I_{DSS}(1 + v_{GS}/V_{po})^2 = I_{DSS}[1 + (V_{GG} - i_{DS}R_s)/V_{po}]^2.$$

$$i_{DS} = (0.001)[1 + (-2.5 - 1000i_{DS})/(5)]^2 = (0.001)[+0.5 - 200i_{DS}]^2$$

$$40{,}000i_{DS}^2 + (-1000 - 200)i_{DS} + 0.25 = 0$$

$$40{,}000i_{DS}^2 + (-1200)i_{DS} + 0.25 = 0$$

$$i_{DS}^2 + (-0.03)i_{DS} + 0.00000625 = 0$$

$$i_{DS} = 0.02979 \text{ A}, \ 0.000209 \text{ A}$$

Kirchhoff's-Voltage-Law on Drain Side (the Load-Line Equation):

$$-V_{DD} + i_{DS} R_s + v_{DS} = 0 \quad \text{or} \quad v_{DS} = V_{DD} - i_{DS}R_s$$

For $i_{DS} = 0.02979$ A,

$$v_{DS} = V_{DD} - i_{DS}R_s = 15 - 29.79 = -14.79 \text{ V}$$

$$v_{GS} = V_{GG} - i_{DS}R_s = -2.5 - 29.79 = -32.29$$

(Does not satisfy needed voltage ranges – not the correct solution)

For $i_{DS} = 0.00209$ A,

$$v_{DS} = V_{DD} - i_{DS}R_s = 15 - 0.209 = 14.79 \text{ V}$$

$$v_{GS} = V_{GG} - i_{DS}R_s = -2.5 - 0.209 = -2.709 \text{ V}$$

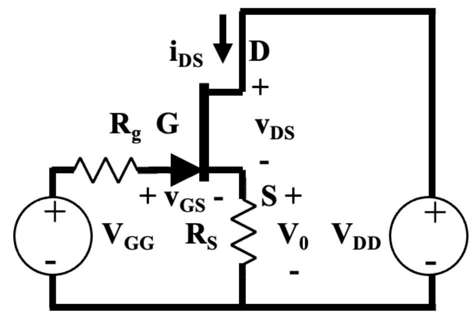
(Satisfies needed voltage ranges – the correct solution)

Operating point

$$v_{DS} = 14.79 \text{ V and } i_{DS} = 0.000209 \text{ A} = 0.209 \text{ mA}$$

Source Follower JFET Circuit Example

Consider a n-channel JFET circuit with V_{po} = 5.0 V, I_{DSS} = 1.0 mA, R_s = 1000 Ω, V_{GG} = - 2.5 V, and V_{DD} = 15 V. (Note that $v_{GS} \neq V_{GG}$.)



Calculate the operating point v_{DS} and i_{DS}.

EE 2200 INTRO. TO ELECTRONIC DEVICES

ECE, Missouri S&T **@ 2023 Steve E. Watkins**

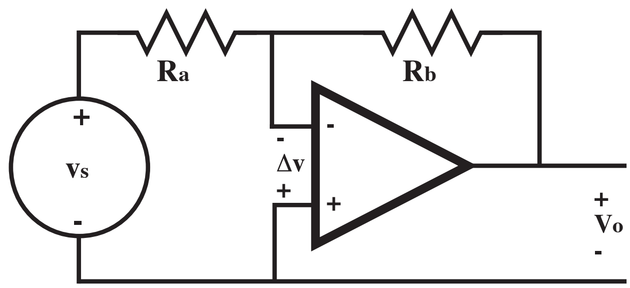
WORKSHEETS
FOR
EXAMINATION 3

Topics Include:
Ideal and Non-Ideal OpAmp Models
OpAmp Circuits
Optoelectronics
Laser Diodes and Photodiodes and Related Circuits

Boltzmann's constant:	$k = 1.381 \times 10^{-23}$ J/K $= 8.618 \times 10^{-5}$ eV/K		
Planck's constant	$h = 4.136 \times 10^{-15}$ eV-sec $= 6.626 \times 10^{-34}$ J-sec		
Electronic charge:	$q = 1.602 \times 10^{-19}$ C		
kT at 300 K	$kT = 0.0259$ eV	eV-J conversion	1 eV $= 1.602 \times 10^{-19}$ J
Free-space permittivity	$\varepsilon_o = 8.854 \times 10^{-14}$ F/cm	Speed of Light	$c = 2.998 \times 10^{10}$ cm/s
Relative permittivity	Si: 11.9	Ge: 16.0	GaAs: 13.1
Bandgap energies	Si: 1.12 eV	Ge: 0.67 eV	GaAs: 1.42 eV

INVERTING OPAMP WITH FINITE GAIN

Consider an inverting OpAmp circuit with an OpAmp gain of A, V_S =+5 V, R_a = 500 Ω, and R_b = 1,000 Ω. Besides the OpAmp gain A, the OpAmp is ideal.



Calculate the output voltage V_0, if A goes to infinity.

Kirchhoff's-Current-Law for the (-) terminal:

(Note that the OpAmp input current is zero)

$(- \Delta v - v_S)/R_a + (- \Delta v - v_o)/R_b = 0$ and $\Delta v = v_o/A$

$(- v_o/A - v_S)/R_a + (- v_o/A - v_o)/R_b = 0$

Hence,

$v_S/R_a = (- 1/AR_a - 1/AR_b - 1/R_b)v_o = (- 1/A)[(R_b + R_a + AR_a)/R_aR_b]v_o$

$v_o = - \{R_b/[(R_b + R_a)/A + R_a]\}v_S$

$\lim_{A \text{ to } \infty} v_o = - (R_b/R_a)v_S$

In the limit

$v_o = - (R_b/R_a)v_S = - (1000/500)(5 \text{ V}) = - 10 \text{ V}$

Calculate the output voltage V_0, if A equals 10,000.

With a finite A, the output is

$v_o = - \{R_b/[(R_b + R_a)/A + R_a]\}v_S$

$v_o = - \{1000/[(1000 + 500)/10{,}000 + 500]\}(5 \text{ V})$

$v_o = - 9.9970 \text{ V}$

Calculate the output voltage V_0, if A equals 100,000.

With a finite A, the output is

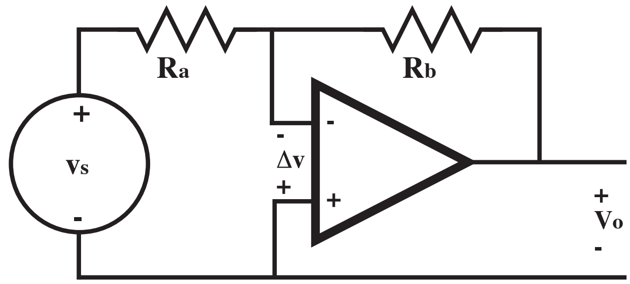
$v_o = - \{R_b/[(R_b + R_a)/A + R_a]\}v_S$

$v_o = - \{1000/[(1000 + 500)/100{,}000 + 500]\}(5 \text{ V})$

$v_o = - 9.9997 \text{ V}$

INVERTING OPAMP WITH FINITE GAIN

Consider an inverting OpAmp circuit with an OpAmp gain of A, V_S =+5 V, R_a = 500 Ω, and R_b = 1,000 Ω. Besides the OpAmp gain A, the OpAmp is ideal.



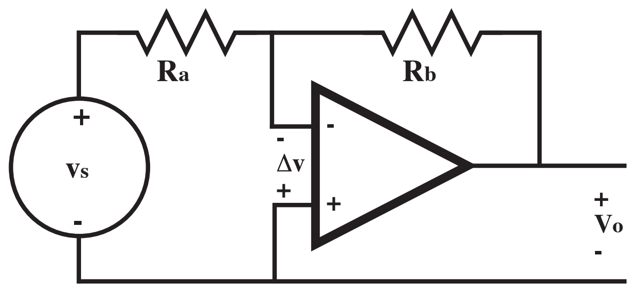
Calculate the output voltage V_0, if A goes to infinity.

Calculate the output voltage V_0, if A equals 10,000.

Calculate the output voltage V_0, if A equals 100,000.

INVERTING OPAMP EXAMPLE

Consider an inverting OpAmp circuit with R_a = 1,000 Ω, R_b = 3,000 Ω, and V_S =+5.0 V, Assume that the OpAmp is ideal.



Calculate the currents through the R_a resistor and through the R_b resistor.

By the prior analysis, the voltage Δv is driven to zero. Hence,

For R_a, $i_a = (- \Delta v - v_S)/R_a = (0 - 5)/(1{,}000) = - 0.005$ A = - 5.0 mA

For R_b, the output voltage must be known,
The prior analysis gives (in the limit)

$v_o = - (R_b/R_a)v_S = - (3000/1000)(5\text{ V}) = - 15\text{ V}$

Then, $i_b = (- \Delta v – v_o)/R_b = (0 + 15)/(3{,}000) = 0.005$ A = 5.0 mA

Calculate the current generated by the OpAmp if a load resistor of $R_L = 1{,}000\ \Omega$ is attached.

As before, the output voltage is

$v_o = - (R_b/R_a)v_S = - (3000/1000)(5\text{ V}) = - 15\text{ V}$

The load current is

$i_L = (v_o)/R_L = (- 15)/(1{,}000) = - 0.015$ A = - 15.0 mA

The current through the resistor network is

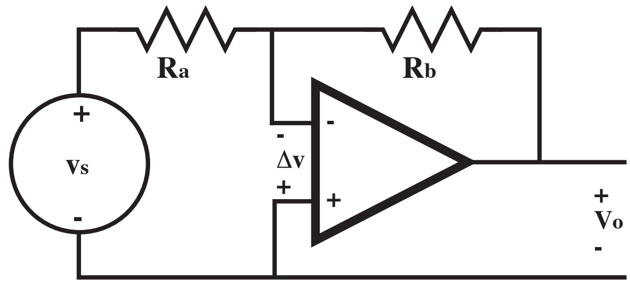
$i_b = (- \Delta v - v_S)/R_b = (0 + 15)/(3{,}000) = 0.005$ A = 5.0 mA

The total current from the OpAmp is

$i_{Total} = i_L - i_b = - 15$ mA – 5.0 mA = - 20 mA

INVERTING OPAMP EXAMPLE

Consider an inverting OpAmp circuit with R_a = 1,000 Ω, R_b = 3,000 Ω, and V_S =+5.0 V, Assume that the OpAmp is ideal.

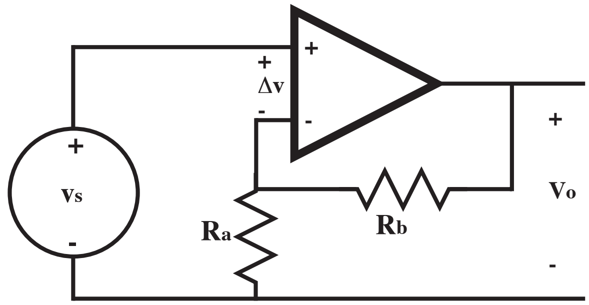


Calculate the currents through the R_a resistor and through the R_b resistor.

Calculate the current generated by the OpAmp if a load resistor of R_L = 1,000 Ω is attached.

NON-INVERTING OPAMP EXAMPLE

Consider a non-inverting OpAmp circuit with $R_a + R_b = R_{Total} = 1.0\ k\Omega$ with $R_a = wR_{Total}$ and $R_b = (1 - w)R_{Total}$. Let V_S =+10.0 mV. Assume that the OpAmp is ideal.



For a gain of 2, calculate the fraction w and the resistor values for R_a and R_b.

Note that $R_a + R_b = R_{Total}$ where $0 < w < 1$

The solution for this configuration is

$v_o/v_S = (R_a + R_b)/R_a = 1 + R_b/R_a = 1 + [(1 - w)R_{Total} /wR_{Total}] =$

$v_o/v_S = 1 + [(1 - w)R_{Total} /wR_{Total}] = 1 + 1/w - 1 = 1/w$

For 2 = 1/w, then w = ½.

Then, $R_a = wR_{Total} = (1/2)1.0\ k\Omega = 0.5\ k\Omega$

and $R_b = (1 - w)R_{Total} = (1/2)1.0\ k\Omega = 0.5\ k\Omega$

Calculate the power dissipated in R_a and R_b.

The output voltage is

$v_o = \{1 + [(1 - w)R_{Total} /wR_{Total}]\}v_S = (1/w)v_S = 2\ (10\ mV) = 20\ mV$

Then, the current through R_{Total} is

$I_{Total} = (v_o)/(R_{aTotal}) = (0.020\ V)/(1.0\ k\Omega) = 0.020\ mA$

And

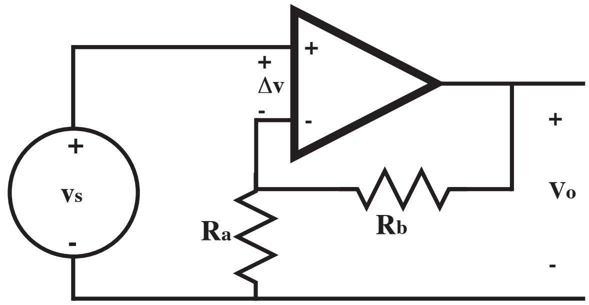
$P_a = P_b = (R_{a,b})(I_{Total})^2 = (0.5\ k\Omega\ )(0.020\ mA)^2 = 0.20\ \mu W$

The total power dissipated in R_a and R_b is

$P_{Total} = P_a + P_b = \ 0.40\ \mu W$

NON-INVERTING OPAMP EXAMPLE

Consider a non-inverting OpAmp circuit with $R_a + R_b = R_{Total} = 1.0\ k\Omega$ with $R_a = wR_{Total}$ and $R_b = (1 - w)R_{Total}$. Let V_S =+10.0 mV. Assume that the OpAmp is ideal.

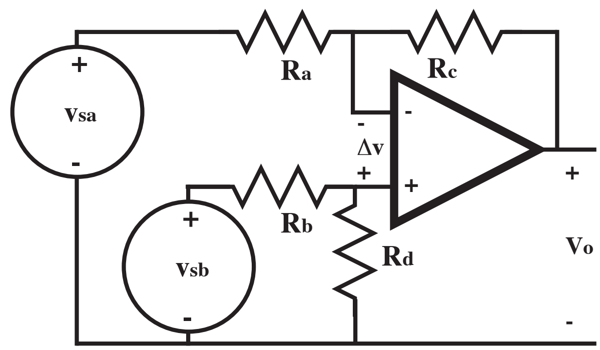


For a gain of 2, calculate the fraction w and the resistor values for R_a and R_b.

Calculate the power dissipated in R_a and R_b.

SUBTRACTOR OPAMP EXAMPLE

Consider a subtractor OpAmp circuit with $R_a = (x)1{,}000\ \Omega$, $R_c = (1 - x)1{,}000\ \Omega$, $R_b = (y)100\ \Omega$, and $R_d = (1 - y)100\ \Omega$ where $0<x<1$ and $0<y<1$. Assume that the OpAmp is ideal.



Calculate the values x and y for which the magnitude of the component gain for input V_{Sa} is 3 and the magnitude of the component gain for input V_{Sb} is also 3.

In the limit, the analysis gives

$$v_o = v_{oa} + v_{ob} = -[R_c/R_a]\,V_{Sa} + \{[1 + (R_c/R_a)] / [1 + (R_b/R_d)]\}\,V_{sb}$$

Hence, for input V_{Sa}

$$|v_{oa}/V_{Sa}| = [R_c/R_a] = [(1 - x)(1000)]/[(x)(1000)] = (1/x - 1) = 3$$
$$x = 0.25$$

Then, $R_a = 250\ \Omega$ and $R_c = 750\ \Omega$

Hence, for input V_{Sa}

$$|v_{ob}/V_{Sb}| = \{[1 + (R_c/R_a)] / [1 + (R_b/R_d)]\}$$
$$|v_{ob}/V_{Sb}| = \{[1 + (750/250)] / [1 + (y)/(1 - y)]\} = (4)/[1 + 1/(1/y - 1)]$$
$$|v_{ob}/V_{Sb}| = (4)/[1 + 1/(1/y - 1)] = 3$$
$$4/3 = 1 + 1/(1/y - 1) \quad \text{or} \quad 4/3 - 1 = 1/(1/y - 1)$$
$$3 = 1/y - 1$$
$$y = 0.25$$

Then, $R_b = 25\ \Omega$ and $R_d = 75\ \Omega$

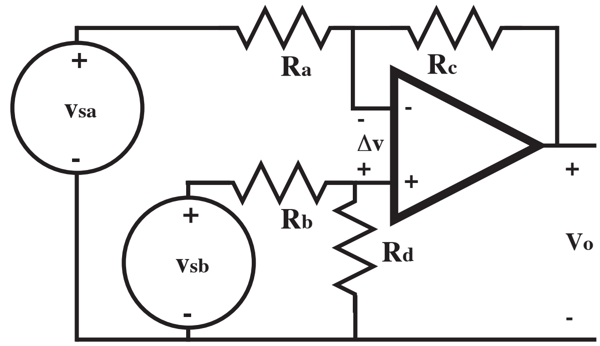
Calculate the output voltage V_0, if $V_{Sa} = 2V$ and $V_{Sb} = 4\ V$.

In the limit, the analysis gives

$$v_o = v_{oa} + v_{ob} = -[R_c/R_a]\,V_{Sa} + \{[1 + (R_c/R_a)] / [1 + (R_b/R_d)]\}\,V_{sb}$$
$$v_o = v_{oa} + v_{ob} = -(3)\,(2\ V) + (3)\,(4\ V) = +6\ V$$
$$v_o = +6\ V$$

SUBTRACTOR OPAMP EXAMPLE

Consider a subtractor OpAmp circuit with R_a = (x)1,000 Ω, R_c = (1 - x)1,000 Ω, R_b = (y)100 Ω, and R_d = (1 - y)100 Ω where 0<x<1 and 0<y<1. Assume that the OpAmp is ideal.



Calculate the values x and y for which the magnitude of the component gain for input V_{Sa} is 3 and the magnitude of the component gain for input V_{Sb} is also 3.

Calculate the output voltage V_0, if V_{Sa} = 2V and V_{Sb} = 4 V.

DESIGN EXAMPLE

Design an OpAmp circuit with a minimum number of ideal OpAmps that has the following characteristics:

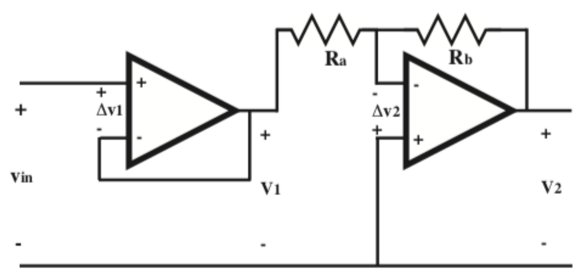
Has an overall signal gain of - 5 and
Draws no current from the input source.

Implementation #1

Stage 1: A Buffer OpAmp Circuit to give a gain of $v_{o1}/v_S = +1$ while drawing no current from the input source.

Stage 2: An Inverting OpAmp Circuit to give a gain of $v_{o2}/v_{o1} = -5$. One possible set of resistors is $R_a = 200\ \Omega$ and $R_b = 1000\ \Omega$, i.e. $-R_b / R_a = -5$.

The overall gain is
$(v_{o2}/v_S) = (v_{o1}/v_S)(v_{o2}/v_{o1})$
$(v_{o2}/v_S) = (+1)(-5) = -5$.

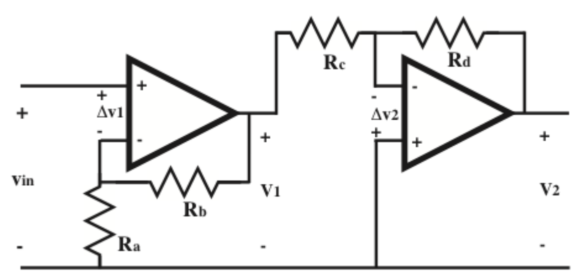


Implementation #2

Stage 1: A Non-inverting OpAmp Circuit to give a gain of $v_{o1}/v_S = +5$ (note this circuit draws no current from the input source). One possible set of resistors is $R_a = 250\ \Omega$ and $R_b = 1000\ \Omega$, i.e. $(1 + R_b / R_a) = +5$.

Stage 2: An Inverting OpAmp Circuit to give a gain of $v_{o2}/v_{o1} = -1$. One possible set of resistors is $R_a = 500\ \Omega$ and $R_b = 500\ \Omega$, i.e. $-R_b / R_a = -1$.

The overall gain is
$(v_{o2}/v_S) = (v_{o1}/v_S)(v_{o2}/v_{o1})$
$(v_{o2}/v_S) = (+5)(-1) = -5$.



OPAMP DESIGN EXAMPLE

Design an OpAmp circuit with a minimum number of ideal OpAmps that has the following characteristics:

Has an overall signal gain of - 5 and

Draws no current from the input source.

Implementation #1

Implementation #2

SEMICONDUCTOR ABSORPTION EXAMPLE

Consider a crystal semiconductor InP. It has an energy gap of $E_G = 1.35$ eV.

Electron Charge	$q = 1.602 \times 10^{-19}$ C
Speed of Light (Vacuum)	$c = 2.998 \times 10^{10}$ cm/s
Planck's Constant	$h = 4.136 \times 10^{-15}$ eV-sec $= 6.626 \times 10^{-34}$ J-sec

Calculate the optical wavelength and frequency associated with a bandgap transition.

The photon energy for a wavelength of light λ is $E_P = hc/\lambda$. A semiconductor will absorb light if the photon energy is greater than or equal to the energy gap E_G. Hence, the maximum wavelength for absorption is
$\lambda = hc/E_G = (4.136 \times 10^{-15}$ eV-sec$)(2.998 \times 10^{10}$ cm/sec$)/(1.35$ eV$)$
$\lambda = 9.185 \times 10^{-5}$ cm $= 0.9185$ µm

$f = c / \lambda = (2.998 \times 10^{10}$ cm/sec$)/(9.185 \times 10^{-5}$ cm$) = 3.264 \times 10^{14}$ Hz

In what part of the optical spectrum is this threshold value?

The infrared portion of the spectrum, or the near infrared.
The divisions of the Infrared spectrum are 0.700 µm to 10^5 µm.

For a 1.0 mW wave at this threshold wavelength, how many photons are present?

The number of photons per second are $P\ \lambda/hc$.
$P\ \lambda/hc = (0.001$ J/sec$)$ $(9.185 \times 10^{-5}$ cm$)$ /
$(6.626 \times 10^{-34}$ J-sec$)(2.998 \times 10^{10}$ cm/sec$)$
$P\ \lambda/hc = (4.624 \times 10^{15}$ photons/sec$)$

SEMICONDUCTOR ABSORPTION EXAMPLE

Consider a crystal semiconductor InP. It has an energy gap of $E_G = 1.35$ eV.

Electron Charge	$q = 1.602 \times 10^{-19}$ C
Speed of Light (Vacuum)	$c = 2.998 \times 10^{10}$ cm/s
Planck's Constant	$h = 4.136 \times 10^{-15}$ eV-sec $= 6.626 \times 10^{-34}$ J-sec

Calculate the optical wavelength and frequency associated with a bandgap transition.

In what part of the optical spectrum is this threshold value?

For a 1.0 mW wave at this threshold wavelength, how many photons are present?

SEMICONDUCTOR ABSORPTION EXAMPLE

A laser beam of irradiance 1.0 W/m^2 is incident upon a silicon (Si) sample. The absorption coefficient α_L at the laser wavelength is 1000 cm^{-1}.

Calculate the thickness in microns (μm) for which the transmitted irradiance is reduced to one half of the initial value, i.e. 0.50 W/m^2. Neglect reflections.

Neglecting reflection, $I = I_o \exp(-\alpha_L x)$. For the given conditions,

$0.50 = 1.0 \exp(-\alpha_L L)$
$L = (-1/\alpha_L)\ln(0.50/1.0) = (-1/1000\ cm^{-1})\ln(0.50) = 0.000693\ cm$
$L = 6.93\ \mu m$

Calculate the thickness in microns (μm) for which the transmitted irradiance is reduced to 0.10 W/m^2. Neglect reflections.

Neglecting reflection, $I = I_o \exp(-\alpha_L x)$. For the given conditions,

$0.10 = 1.0 \exp(-\alpha_L L)$
$L = (-1/\alpha_L)\ln(0.10/1.0) = (-1/1000\ cm^{-1})\ln(0.10) = 0.00230\ cm$
$L = 23.0\ \mu m$

Calculate the thickness in microns (μm) for which the transmitted irradiance is reduced to 0.010 W/m^2. Neglect reflections.

Neglecting reflection, $I = I_o \exp(-\alpha_L x)$. For the given conditions,

$0.50 = 1.0 \exp(-\alpha_L L)$
$L = (-1/\alpha_L)\ln(0.01/1.0) = (-1/1000\ cm^{-1})\ln(0.01) = 0.00461\ cm$
$L = 46.1\ \mu m$

SEMICONDUCTOR ABSORPTION EXAMPLE

A laser beam of irradiance 1.0 W/m^2 is incident upon a silicon (Si) sample. The absorption coefficient α_L at the laser wavelength is 1000 cm^{-1}.

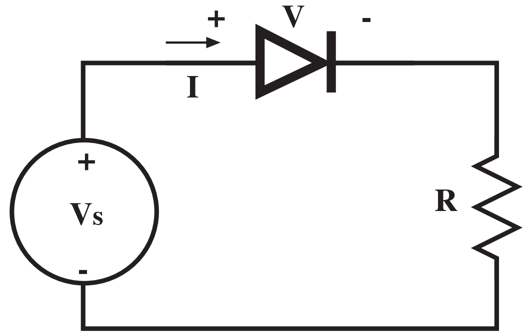
Calculate the thickness in microns (μm) for which the transmitted irradiance is reduced to one half of the initial value, i.e. 0.50 W/m^2. Neglect reflections.

Calculate the thickness in microns (μm) for which the transmitted irradiance is reduced to 0.10 W/m^2. Neglect reflections.

Calculate the thickness in microns (μm) for which the transmitted irradiance is reduced to 0.010 W/m^2. Neglect reflections.

APD EXAMPLE

A Si avalanche photodiode is reverse-biased for source voltage $V_S = -80.0$ V. The reverse saturation current is 0.010 mA and the $\lambda = 900$ nm. Assume $|V| >> kT/q$. The resistance is $R = 20.0\ k\Omega$.



If the optical power is 0.10 mW, calculate the needed quantum efficiency (including the avalanche gain) to produce a diode current of - 1.0 mA.

If the diode current is – 1.0 mA, then I_{Light} is

$$I = I_o\,[\exp(qV_d/kT) - 1] - I_{light} = -(0.010\text{ mA}) - I_{light} = -1.0\text{ mA}$$

$$I_{light} = -(0.010\text{ mA}) + 1.0\text{ mA} = +0.99\text{ mA}$$

Then, $I_{light} = \eta q P \lambda/hc$ or

$$\eta = I_{light}\, hc/(\lambda q P)$$

$$\eta = (0.99 \times 10^{-3}\text{ C/s})(6.626 \times 10^{-34}\text{ J-s})(2.998 \times 10^{10}\text{ cm/s}) \,/\, [(0.9 \times 10^{-4}\text{ cm})(1.602 \times 10^{-19}\text{ C})(0.0001\text{ J/s})]$$

$$\eta = I_{light}\, hc/(\lambda q P) = 13.6$$

For the diode current of - 1.0 mA, calculate the diode voltage.

The circuit load-line equation is

$$-V_S + V_d + IR = 0$$

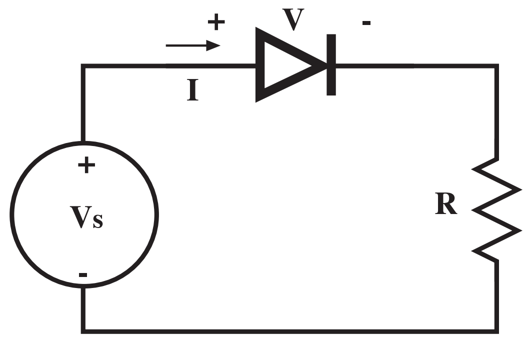
$$V_d = +V_S - IR = (-80) - (-1.0\text{ mA})(20.0\ k\Omega)$$

$$V_d = -60.0\text{ V}$$

The operating point is $V_d = -60.0$ V and $I = -1.0$ mA

APD EXAMPLE

A Si avalanche photodiode is reverse-biased for source voltage V_S = - 80.0 V. The reverse saturation current is 0.010 mA and the λ = 900 nm. Assume $|V| >> kT/q$. The resistance is R = 20.0 kΩ.



If the optical power is 0.10 mW, calculate the needed quantum efficiency (including the avalanche gain) to produce a diode current of - 1.0 mA.

For the diode current of - 1.0 mA, calculate the diode voltage.

