INTERNATIONAL SIXTH EDITION

SEDRA/SMITH

INSTRUCTOR'S SOLUTIONS MANUAL FOR
MICROELECTRONIC CIRCUITS

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This Instructor's Solutions Manual contains complete solutions for the 1000+ end-of-chapter problems created specifically for the International Sixth Edition of Sedra/Smith's *Microelectronic Circuits*.

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Contents

Preface

This manual contains complete solutions for all exercises and end-of-chapter problems included in the book *Microelectronic Circuits, International Sixth Edition*, by Adel S. Sedra and Kenneth C. Smith.

We are grateful to Mandana Amiri, Shahriar Mirabbasi, Roberto Rosales, Alok Berry, Norman Cox, John Wilson, Clark Kinnaird, Roger King, Marc Cahay, Kathleen Muhonen, Angela Rasmussen, Mike Green, John Davis, Dan Moore, and Bob Krueger, who assisted in the preparation of this manual. We also acknowledge the contribution of Ralph Duncan and Brian Silveira to previous editions of this manual.

Communications concerning detected errors should be sent to the attention of the Engineering Editor, mail to Oxford University Press, 198 Madison Avenue, New York, New York, USA 10016 or e-mail to higher.education.us@oup.com. Needless to say, they would be greatly appreciated.

A website for the book is available at www.oup.com/sedra-xse

Ex: 1.1 When output terminals are open circuited

For circuit a. $v_{OC} = v_s(t)$

For circuit b. $v_{OC} = i_s(t) \times R_s$

When output terminals are short-circuited

For circuit a. $i_{sc} = \dfrac{v_S(t)}{R_S}$

For circuit b. $i_{sc} = i_S(t)$

For equivalency

$R_S i_S(t) = v_S(t)$

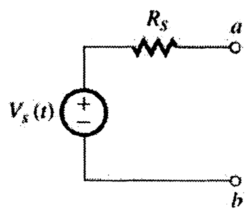


Figure 1.1a

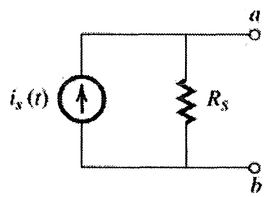
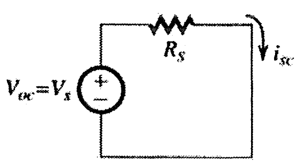


Figure 1.1b

Ex: 1.2

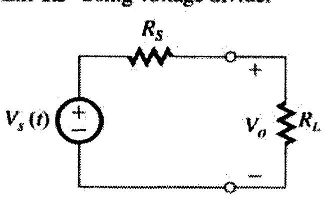


$V_{OC} = 10$ mV

$i_{SC} = 10\ \mu$A

$$R = \frac{V}{i} = \frac{10\text{ mV}}{10\ \mu\text{A}} = 1\text{ k}\Omega$$

Ex: 1.3 Using voltage divider



$$v_o(t) = v_S(t) \times \frac{R_L}{R_S + R_L}$$

Given $v_S(t) = 10$ mV and $R_S = 1$ kΩ

If $R_L = 100$ kΩ

$$v_O = 10\text{ mV} \times \frac{100}{100 + 1} = 9.9\text{ mV}$$

If $R_L = 10$ kΩ

$$v_O = 10\text{ mV} \times \frac{10}{10 + 1} \simeq 9.1\text{ mV}$$

If $R_L = 1$ kΩ

$$v_O = 10\text{ mV} \times \frac{1}{1 + 1} = 5\text{ mV}$$

If $R_L = 100\ \Omega$

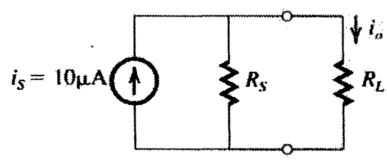
$$v_O = 10\text{ mV} \times \frac{100}{100 + 1\text{ K}} \simeq 0.91\text{ V}$$

$$80\%\text{ of source voltage} = 10\text{ mV} \times \frac{80}{100} = 8\text{ mV}$$

If R_L gives 8 mV when $R_S = 1$ kΩ, then

$$8 = 10 \times \frac{R_L}{1 + R_L} \Rightarrow R_L = 4\text{ k}\Omega$$

Ex: 1.4 Using current divider



$$i_O = i_S \times \frac{R_S}{R_S + R_L}$$

Given $i_S = 10\ \mu$A, $R_S = 100$ kΩ

For

$$R_L = 1\text{ k}\Omega,\ i_O = 10\ \mu\text{A} \times \frac{100}{100 + 1} = 9.9\ \mu\text{A}$$

$$\text{For } R_L = 10\text{ k}\Omega,\ i_O = 10\ \mu\text{A} \times \frac{100}{100 + 10}$$

$\simeq 9.1\ \mu$A

For

$$R_L = 100\text{ k}\Omega,\ i_O = 10\ \mu\text{A} \times \frac{100}{100 + 100} = 5\ \mu\text{A}$$

For

$$R_L = 1\text{ M}\Omega,\ i_O = 10\ \mu\text{A} \times \frac{100\text{ K}}{100\text{ K} + 1\text{ M}}$$

$\simeq 0.9\ \mu$A

$$80\%\text{ of source current} = 10 \times \frac{80}{100} = 8\ \mu\text{A}$$

If a load R_L gives 80% of the source current, then

$$8\ \mu\text{A} = 10\ \mu\text{A} \times \frac{100}{100 + R_L}$$

$$\Rightarrow R_L = 25\text{ k}\Omega$$

Ex: 1.5 $f = \frac{1}{T} = \frac{1}{10^{-3}} = 1000$ Hz

$\omega = 2\pi f = 2\pi \times 10^3$ rad/s

Ex: 1.6 (a) $T = \frac{1}{f} = \frac{1}{60}\text{s} = 16.7$ ms

(b) $T = \frac{1}{f} = \frac{1}{10^{-3}} = 1000$ s

(c) $T = \frac{1}{f} = \frac{1}{10^6}\text{s} = 1\ \mu\text{s}$

Ex: 1.7 If 6 MHz is allocated for each channel, then 470 MHz to 806 MHz will accomodate

$\frac{806 - 470}{6} = 56$ channels

Since it starts with channel 14, it will go from channel 14 to channel 69

Ex: 1.8 $P = \frac{1}{T}\int_0^T \frac{v^2}{R}dt$

$= \frac{1}{T} \times \frac{V^2}{R} \times T = \frac{V^2}{R}$

Alteratively,

$P = P_1 + P_3 + P_5 + \ldots$

$= \left(\frac{4V}{\sqrt{2}\pi}\right)^2 \frac{1}{R} + \left(\frac{4V}{3\sqrt{2}\pi}\right)^2 \frac{1}{R} + \left(\frac{4V}{5\sqrt{2}\pi}\right)^2 \frac{1}{R} + \ldots$

$= \frac{V^2}{R} \times \frac{8}{\pi^2} \times \left(1 + \frac{1}{9} + \frac{1}{25} + \frac{1}{49} + \ldots\right)$

It can be shown by direct calculation that the infinite series in the parentheses has a sum that approaches $\pi^2/8$; thus P becomes V^2/R as found from direct calculation.

Fraction of energy in fundamental

$= 8/\pi^2 = 0.81$

Fraction of energy in first five harmonics

$= \frac{8}{\pi^2}\left(1 + \frac{1}{9} + \frac{1}{25}\right) = 0.93$

Fraction of energy in first seven harmonics

$= \frac{8}{\pi^2}\left(1 + \frac{1}{9} + \frac{1}{25} + \frac{1}{49}\right) = 0.95$

Fraction of energy in first nine harmonics

$5\frac{8}{\pi^2}\left(1 + \frac{1}{9} + \frac{1}{25} + \frac{1}{49} + \frac{1}{81}\right) = 0.96$

Note that 90% of the energy of the square wave is in the first three harmonics; that is, in the fundamental and the third harmonic.

Ex: 1.9 (a) D can represent 15 distinct values between 0 and +15 V. Thus,

$v_A = 0\text{ V} \Rightarrow D = 0000$

$v_A = 1\text{ V} \Rightarrow D = 0001$

$v_A = 2\text{ V} \Rightarrow D = 0010$

$v_A = 15\text{ V} \Rightarrow D = 1111$

(b) (i) +1 V (ii) +2 V (iii) +4 V (iv) +8 V

(c) The closest discrete value represented by D is 5 V; thus $D = 0101$. The error is -0.2 V or $-0.2/5.2 \times 100 = -4\%$

Ex: 1.10 Voltage gain = 20 log 100 = 40 dB

Current gain = 20 log 1000 = 60 dB

Power gain = $10 \log A_p = 10 \log (A_v A_i)$

$= 10 \log 10^5 = 50$ dB

Ex: 1.11 $P_{dc} = 15 \times 8 = 120$ mW

$P_L = \frac{(6/\sqrt{2})^2}{1} = 18$ mW

$P_{\text{dissipated}} = 120 - 18 = 102$ mW

$\eta = \frac{P_L}{P_{dc}} \times 100 = \frac{18}{120} \times 100 = 15\%$

Ex: 1.12

$v_o = 1 \times \frac{10}{10^6 + 10} \simeq 10^{-5}\text{ V} = 10\ \mu\text{V}$

$P_L = v_O^2/R_L = \frac{(10 \times 10^{-6})^2}{10} = 10^{-11}$ W

With the buffer amplifier:

$v_O = 1 \times \frac{R_i}{R_i + R_S} \times A_{vo} \times \frac{R_L}{R_L + R_o}$

$= 1 \times \frac{1}{1+1} \times 1 \times \frac{10}{10 + 10} = 0.25$ V

$P_L = \frac{v_O^2}{R_L} = \frac{0.25^2}{10} = 6.25$ mW

Voltage gain $= \frac{v_O}{v_S} = \frac{0.25\text{ V}}{1\text{ V}} = 0.25$ V/V

$= -12$ dB

Power gain $(A_p) \equiv \frac{P_L}{P_i}$

where $P_L = 6.25$ mW and $P_i = v_i i_1$.

$v_i = 0.5$ V and

$i_i = \frac{1\text{ V}}{1\text{ M}\Omega + 1\text{ M}\Omega} = 0.5\ \mu\text{A}$

Thus,

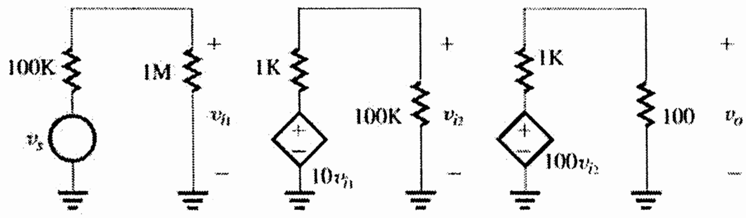
$P_i = 0.5 \times 0.5 = 0.25\ \mu\text{W}$

and,

$A_p = \frac{6.25 \times 10^{-3}}{0.25 \times 10^{-6}} = 25 \times 10^3$

$10 \log A_p = 44$ dB

This figure belongs to Exercise 1.15



Ex: 1.13 Open-circuit (no load) output voltage $= A_{v_o} v_i$

Output voltage with load connected

$$= A_{v_o} v_i \frac{R_L}{R_L + R_O}$$

$$0.8 = \frac{1}{R_O + 1} \Rightarrow R_O = 0.25 \text{ k}\Omega = 250\ \Omega$$

Ex: 1.14 $A_{v_o} = 40 \text{ dB} = 100 \text{ V/V}$

$$P_L = \frac{v_O^2}{R_L} = \left(A_{vo} v_i \frac{R_L}{R_L + R_O}\right)^2 / R_L$$

$$= v_i^2 \times \left(100 \times \frac{1}{1+1}\right)^2 / 1000 = 2.5 v_i^2$$

$$P_i = \frac{v_i^2}{R_i} = \frac{v_i^2}{10{,}000}$$

$$A_p = \frac{P_L}{P_i} = \frac{2.5 v_i^2}{10^{-4} v_i^2} = 2.5 \times 10^4 \text{ W/W}$$

$10 \log A_p = 44$ dB

Ex: 1.15 Without stage 3 (see figure above)

$$\frac{v_0}{v_S} = \left(\frac{1 \text{ M}}{100 \text{ K} + 1 \text{ M}}\right)(10)\left(\frac{100 \text{ K}}{100 \text{ K} + 1 \text{ K}}\right)$$

$$\times (100)\left(\frac{100}{100 + 1 \text{ K}}\right)$$

$$\frac{v_0}{v_S} = (0.909)(10)(0.9901)(100)(0.0909) = 81.8 \text{ V}$$

Ex: 1.16 Given $v_s = 1$ mV

$$\frac{v_{i1}}{v_s} = 0.909 \text{ So}$$

$$v_{i1} = 0.909\, v_S = 0.909 \times 1 = 0.909 \text{ mV}$$

$$\frac{v_{i2}}{v_s} = \frac{v_{i2}}{V_{i1}} \times \frac{v_{i1}}{V_S} = 9.9 \times 0.909 = 9 \text{ V/V}$$

For $v_s = 1$ mV

$$v_{i2} = 9 \times v_S = 9 \times 1 = 9 \text{ mV}$$

$$\frac{v_{i3}}{v_s} = \frac{v_{i3}}{v_{i2}} \times \frac{v_{i2}}{v_{i1}} \times \frac{v_{i1}}{v_S} = 90.9 \times 9.9 \times 0.909$$

$= 818$ V/V

For $v_s = 1$ mV

$$v_{i3} = 818\, v_S = 818 \times 1 = 818 \text{ mV}$$

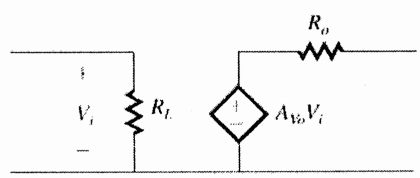
$$\frac{v_{iL}}{v_S} = \frac{v_{iL}}{v_{i3}} \times \frac{v_{i3}}{v_{i2}} \times \frac{v_{i2}}{v_{i1}} \times \frac{v_{i1}}{v_S}$$

$$= 0.909 \times 90.9 \times 9.9 \times 0.909 \simeq 744$$

For $V_s = 1$ mV

$$V_{iL} = 744 \times 1 \text{ mV} = 744 \text{ mV}$$

Ex: 1.17 Using voltage amplifier model, it can be represented as



$R_i = 1$ MΩ

$R_o = 10\ \Omega$

$$A_{vo} = A_{v1} \times A_{v2} = 9.9 \times 90.9 = 900 \text{ V/V}$$

The overall voltage gain

$$\frac{V_O}{V_S} = \frac{R_i}{R_i + R_S} \times A_{vo} \times \frac{R_L}{R_L + R_o}$$

For $R_L = 10\ \Omega$

Overall voltage gain

$$= \frac{1 \text{ M}}{1 \text{ M} + 100 \text{ K}} \times 900 \times \frac{10}{10 + 10} = 409 \text{ V/V}$$

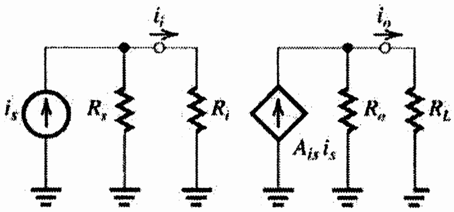
For $R_L = 1000\ \Omega$

Overall voltage gain

$$= \frac{1 \text{ M}}{1 \text{ M} + 100 \text{ K}} \times 900 \times \frac{1000}{1000 + 10} = 810 \text{ V/V}$$

∴ Range of voltage gain is from 409 to 810 V/V

Ex: 1.18



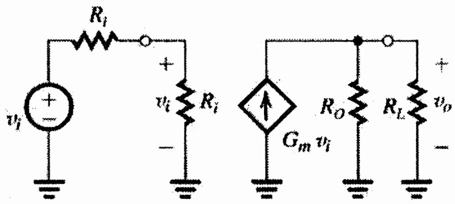
$$i_i = i_S\frac{R_S}{R_S + R_i}$$

$$i_O = A_{is}i_i\frac{R_O}{R_O + R_L} = A_{is}i_S\frac{R_S}{R_S + R_i}\frac{R_O}{R_O + R_L}$$

Thus,

$$\frac{i_O}{i_S} = A_{is}\frac{R_s}{R_S + R_i}\frac{R_O}{R_O + R_L}$$

Ex: 1.19



$$v_i = v_S\frac{R_i}{R_i + R_s}$$

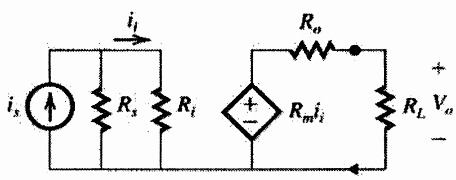
$$v_S = G_m v_i(R_O \parallel R_L)$$

$$= G_m v_S\frac{R_i}{R_i + R_S}(R_O \parallel R_L)$$

Thus,

$$\frac{v_O}{v_S} = G_m\frac{R_i}{R_i + R_S}(R_O \parallel R_L)$$

Ex: 1.20 Using transresistance circuit model the circuit will be



$$\frac{i_i}{i_S} = \frac{R_S}{R_i + R_S}$$

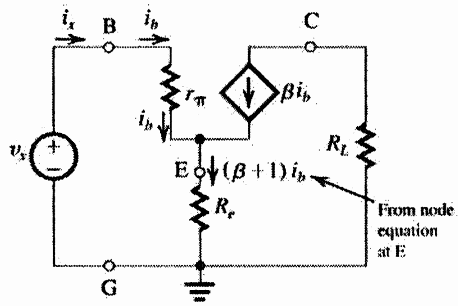
$$V_O = R_m i_i \times \frac{R_L}{R_L + R_O}$$

$$\frac{V_O}{i_i} = R_m\frac{R_L}{R_L + R_O}$$

Now $\frac{V_O}{i_S} = \frac{V_O}{i_i} \times \frac{i_i}{i_S} = R_m\frac{R_L}{R_L + R_O} \times \frac{R_S}{R_i + R_S}$

$$= R_m\frac{R_S}{R_S + R_i} \times \frac{R_L}{R_L + R_O}$$

Ex: 1.21



$$v_b = i_b r_\pi + (\beta + 1)i_b R_e$$

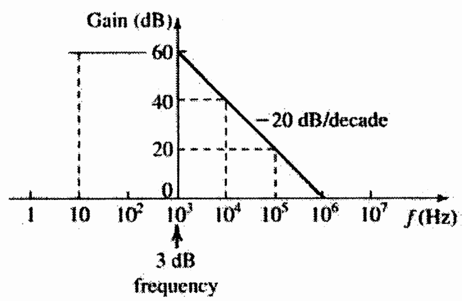
$$= i_b[r_\pi + (\beta + 1)R_e]$$

But $v_b = v_x$ and $i_b = i_x$, thus

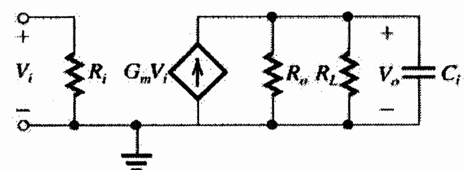
$$R_{in} \equiv \frac{v_x}{i_x} = \frac{v_b}{i_b} = r_\pi + (\beta + 1)R_e$$

Ex: 1.22

f	**Gain**
10 Hz	60 dB
10 kHz	40 dB
100 kHz	20 dB
1 MHz	0 dB



Ex: 1.23



$$V_O = G_m V_i[R_O \parallel R_L \parallel C_L]$$

$$= \frac{G_m V_i}{\frac{1}{R_O} + \frac{1}{R_L} + sC_L}$$

Thus, $\frac{V_O}{V_i} = \frac{G_m}{\frac{1}{R_O} + \frac{1}{R_L}}\frac{1}{1 + \frac{sC_L}{\frac{1}{R_O} + \frac{1}{R_L}}}$

which is of the STC LP type.

DC gain $= \frac{G_m}{\frac{1}{R_O} + \frac{1}{R_L}} \geq 100$

$$\frac{1}{R_O} + \frac{1}{R_L} \le \frac{G_m}{100} = \frac{10}{100} = 0.1 \text{ mA/V}$$

$$\frac{1}{R_L} \le 0.1 - \frac{1}{50} = 0.08 \text{ mA/V}$$

$$R_L \ge \frac{1}{0.08} \text{ k}\Omega = 12.5 \text{ k}\Omega$$

$$\omega_O = \frac{1}{C_L}\left(\frac{1}{R_O} + \frac{1}{R_L}\right) \ge 2\pi \times 100 \text{ kHz}$$

$$C_L \le \frac{\left(\frac{1}{50 \times 10^3} + \frac{1}{12.5 \times 10^3}\right)}{2\pi \times 10^5} = 159.2 \text{ pF}$$

Ex: 1.24 Refer to Fig. E1.23

$$\frac{V_2}{V_S} = \frac{R_i}{R_s + \frac{1}{sC} + R_i} = \frac{R_i}{R_S + R_i} \frac{s}{s + \frac{1}{C(R_S + R_i)}}$$

which is a HP STC function.

$$f_{3\text{dB}} = \frac{1}{2\pi C(R_S + R_i)} \le 100 \text{ Hz}$$

$$C \ge \frac{1}{2\pi(1 + 9)10^3 \times 100} = 0.16 \ \mu\text{F}$$

Ex: 1.25

T = 50 K

$n_i = BT^{3/2}e^{-Eg/(2KT)}$

$= 7.3 \times 10^{15}(50)^{3/2}\, e^{-1.12/(2 \times 8.62 \times 10^{-5} \times 50)}$

$\simeq 9.6 \times 10^{-39}/\text{cm}^3$

T = 350 K

$n_i = BT^{3/2}e^{-Eg/(2KT)}$

$= 7.3 \times 10^{15}(350)^{3/2}\, e^{-1.12/(2 \times 8.62 \times 10^{-5} \times 350)}$

$= 4.15 \times 10^{11}/\text{cm}^3$

Ex: 1.26

$N_D = 10^{17}/\text{cm}^3$

From Exercise 3.1 n_i at

$T = 350\text{ K} = 4.15 \times 10^{11}/\text{cm}^3$

$n_n = N_D = 10^{17}/\text{cm}^3$

$p_n \cong \dfrac{ni^2}{N_D}$

$= \dfrac{(4.15 \times 10^{11})^2}{10^{17}}$

$= 1.72 \times 10^6/\text{cm}^3$

Ex: 1.27

At 300 K, $n_i = 1.5 \times 10^{10}/\text{cm}^3$

$p_p = N_A$

Want electron concentration

$= n_p = \dfrac{1.5 \times 10^{10}}{10^6} = 1.5 \times 10^4/\text{cm}^3$

$\therefore N_A = p_p = \dfrac{ni^2}{n_p}$

$= \dfrac{(1.5 \times 10^{10})^2}{1.5 \times 10^4}$

$= 1.5 \times 10^{16}/\text{cm}^3$

Ex: 1.28

a. υ_n-drift $= -\mu_n E$

Here negative sign indicates that electrons move in a direction opposite to E

We use

υ_n-drift $= -\mu_n E$

$= 1350 \times \dfrac{1}{2 \times 10^{-4}}$ $\because 1\ \mu\text{m} = 10^{-4}$ cm

$= 6.75 \times 10^6\text{ cm/s} = 6.75 \times 10^4\text{ m/s}$

b. Time taken to cross 2 μm

length $= \dfrac{2 \times 10^6}{6.75 \times 10^4} \simeq 30$ ps

c. In n-si drift current density J_n in

$J_n = qn\mu_n E$

$= 1.6 \times 10^{-19} \times 10^{16} \times 1350 \times \dfrac{1\text{ V}}{2 \times 10^{-4}}$

$= 1.08 \times 10^4\text{ A/cm}^2$

d. Drift current $I_n = Aqn\,\upsilon_n$-drift

$= Aqn\mu_n E$

$= 0.25 \times 10^{-8} \times 1.08 \times 10^4$

$= 27\ \mu\text{A}$

Note $0.25\ \mu\text{m}^2 = 0.25 \times 10^{-8}\text{ cm}^2$

Ex: 1.29 $J_n = q D_n \dfrac{dn(x)}{dx}$

From Figure E1.29

$n_O = 10^{17}/\text{cm}^3 = 10^5/(\mu\text{m})^3$

$D_n = 35\text{ cm}^3/\text{s} = 35 \times (10^4)^2(\mu\text{m})^2/\text{s}$

$= 35 \times 10^8(\mu\text{m})^2/\text{s}$

$\dfrac{dn}{dx} = \dfrac{10^5 - 0}{1} = 10^5\mu\text{m}^{-2}$

$J_n = qD_n\dfrac{dn(x)}{dx}$

$= 1.6 \times 10^{-19} \times 35 \times 10^8 \times 10^5$

$= 56 \times 10^{-6}\text{ A}/(\mu\text{m})^2$

$= 56\ \mu\text{ A}/(\mu\text{m})^2$

For $I_n = 1\text{ mA} = J_n \times A$

$\Rightarrow A = \dfrac{1\text{ mA}}{J_n} = \dfrac{10^3\ \mu A}{56\ \mu\text{A}/(\mu\text{m})^2} \simeq 18\ \mu\text{m}^2$

Ex: 1.30

Using equation 1.45

$\dfrac{D_n}{\mu_n} = \dfrac{D_p}{\mu_p} = V_T$

$D_n = \mu_n V_T = 1350 \times 25.9 \times 10^{-3}$

$\cong 35\text{ cm}^2/\text{s}$

$D_p = \mu_p V_T = 480 \times 25.9 \times 10^{-3}$

$\cong 12.4\text{ cm}^2/\text{s}$

Ex: 1.31

Equation 3.50

$W = \sqrt{\dfrac{2\epsilon_S}{q}\left(\dfrac{1}{N_A} + \dfrac{1}{N_D}\right)V_O}$

$$= \sqrt{\frac{2\epsilon_S}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)V_O}$$

$$W^2 = \frac{2\epsilon_S}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)V_O$$

$$V_O = \frac{1}{2}\left(\frac{q}{\epsilon_S}\right) = \left(\frac{N_A N_D}{N_A+N_D}\right)W^2$$

Ex: 1.32

In a p^+ n diode $N_A >> N_D$

Equation 1.50 $W = \sqrt{\frac{2\epsilon_S}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)V_O}$

We can neglect the term $\frac{1}{N_A}$ as Compared to $\frac{1}{N_D}$

since $N_A >> N_D$

$$\simeq \sqrt{\frac{2\epsilon_S}{qN_D}\cdot V_O}$$

Equation 1.51 $X_n = W\frac{N_A}{N_A+N_D}$

$$\simeq W\frac{N_D}{N_D}$$

$$= W$$

Equation 1.52 $X_p = W\frac{N_A}{N_A+N_D}$

since $N_A >> N_D$

$$\simeq W\frac{N_D}{N_A} = W/\left(\frac{N_A}{N_D}\right)$$

Equation 1.53 $Q_J = Aq\left(\frac{N_A N_D}{N_A+N_D}\right)$

$W \simeq Aq\frac{N_A N_D}{N_A}\cdot W$ since $N_A >> N_D$

$$\simeq AqN_D W$$

Equation 1.54 $Q_J = A\sqrt{2\epsilon_S q\left(\frac{N_A N_D}{N_A+N_D}\right)V_O}$

$\simeq A\sqrt{2\epsilon_S q\left(\frac{N_A N_D}{N_A}\right)V_O}$ since $N_A >> N_D$

$$= A\sqrt{2\epsilon_S q N_D V_O}$$

Ex: 1.33

In example 1.29 $N_A = 10^{18}/\text{cm}^3$ and

$N_D = 10^{16}/\text{cm}^3$

In the n-region of this pn juction diode

$$n_n = N_D = 10^{16}/\text{cm}^3$$

$$p_n = \frac{n_i^2}{n_n} = \frac{(1.5\times 10^{10})^2}{10^{16}} = 2.25\times 10^4/\text{cm}^3$$

As one can see from above equation, to increase minority carrier-concentration (p_n) by a factor of 2, one must lower N_D ($= n_n$) by a factor of 2.

Ex: 1.34

Equation 1.38 $I_S = Aqn_i^2\left(\frac{D_p}{L_p N_D}+\frac{D_n}{L_n N_A}\right)$

since $\frac{D_p}{L_p}$ and $\frac{D_n}{L_n}$ here approximately

similar values, if $N_A >> N_D$, then the term $\frac{D_n}{L_n N_A}$

can be neglected as compared to $\frac{D_p}{L_p N_D}$

$$\therefore I_S \cong Aqn_i^2\frac{D_p}{L_p N_D}$$

Ex: 1.35

$$I_S = Aqn_i^2\left(\frac{D_p}{L_p N_D}+\frac{D_n}{L_n N_A}\right)$$

$$= 10^{-4}\times 1.6\times 10^{-19}\times(1.5\times 10^{1})^2$$

$$\times\left(\frac{10}{5\times 10^{-4}\times\frac{10^{16}}{2}}+\frac{10}{10\times 10^{-4}\times 10^{18}}\right)$$

$$= 1.45\times 10^{-14}\text{ A}$$

$$I = I_S(e^{V/V_T}-1)$$

$$\simeq I_S e^{V/V_T} = 1.45\times 10^{-14}e^{0.605/(25.9\times 10^{-3})}$$

$$\simeq 0.2\text{ mA}$$

Ex: 1.36

$$W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_O - V_F)}$$

$$= \sqrt{\frac{2\times 1.04\times 10^{-12}}{1.6\times 10^{-19}}\left(\frac{1}{10^{18}}+\frac{1}{10^{16}}\right)(0.814-0.605)}$$

$$= 1.66\times 10^{-5}\text{ cm} = 0.166\ \mu\text{m}$$

Ex: 1.37

$$W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_O + V_R)}$$

$$= \sqrt{\frac{2\times 1.04\times 10^{-12}}{1.6\times 10^{-19}}\left(\frac{1}{10^{18}}+\frac{1}{10^{16}}\right)(0.814+2)}$$

$$= 6.08\times 10^{-5}\text{ cm} = 0.608\ \mu\text{m}$$

Using equation 1.53

$$Q_J = \text{Aq}\left(\frac{N_A N_D}{N_A+N_D}\right)\text{W}$$

$= 10^{-4} \times 1.6 \times 10^{-19}\left(\frac{10^{18} \times 10^{16}}{10^{18} + 10^{16}}\right) \times 6.08 \times 10^{-5}$ cm

$= 9.63\ pC$

Reverse Current $I = I_S = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)$

$= 10^{-14} \times 1.6 \times 10^{-19} \times (1.5 \times 10^{10})^2$

$\times\left(\frac{10}{5 \times 10^{-4} \times 10^{16}} + \frac{18}{10 \times 10^{-4} \times 10^{18}}\right)$

$= 7.3 \times 10^{-15}$ A

Ex: 1.38

Equation 1.72

$$C_{jo} = A\sqrt{\left(\frac{\epsilon_S q}{2}\right)\left(\frac{N_AN_D}{N_A + N_D}\right)\left(\frac{1}{V_O}\right)}$$

$$= 10^{-4}\sqrt{\left(\frac{1.04 \times 10^{-12} \times 1.6 \times 10^{-19}}{2}\right)}$$

$$\sqrt{\left(\frac{10^{18} \times 10^{16}}{10^{18} + 10^{16}}\right)\left(\frac{1}{0.814}\right)}$$

$= 3.2\ pF$

Equation 1.71

$$C_j = \frac{C_{jO}}{\sqrt{1 + \frac{V_R}{V_O}}}$$

$$= \frac{3.2 \times 10^{-12}}{\sqrt{1 + \frac{2}{0.814}}}$$

$= 1.72\ pF$

Ex: 1.39

$$C_d = \frac{dQ}{dV} = \frac{d}{dV}(\tau_T I)$$

$$= \frac{d}{dv}[\tau_T \times I_S(e^{V/V_T} - 1)]$$

$$= \tau_T I_S \frac{d}{dV}(e^{V/V_T} - 1)$$

$$= \tau_T I_S \frac{1}{V_T} e^{V/V_T}$$

$$= \frac{\tau_T}{V_T} \times I_S e^{V/V_T}$$

$$= \left(\frac{\tau_T}{V_T}\right) I$$

Ex: 1.40

Equation 1.74

$$\tau_p = \frac{L_p^2}{D_p}$$

$$= \frac{(5 \times 10^{-4})^2}{5}$$

$= 25\ ns$

Equation 1.81

$$C_d = \left(\frac{\tau_T}{V_T}\right) I$$

In example 1.30 $N_A = 10^{18}/cm^3$,

$N_D = 10^{16}/cm^3$

Assuming $N_A >> N_D$

$\tau_T \simeq \tau_p = 25\ ns$

$$\therefore C_d = \left(\frac{25 \times 10^{-9}}{25.9 \times 10^{-3}}\right) 0.1 \times 10^{-3}$$

$= 96.5\ pF$

Ex: 2.1

The minimum number of terminals required by a single op amp is five: two input terminals, one output terminal, one terminal for positive power supply and one terminal for negative power supply.

The minimum number of terminals required by a quad op amp is 14: each op amp requires two input terminals and one output terminal (accounting for 12 terminals for the four op amps). In addition, the four op amp can all share one terminal for positive power supply and one terminal for negative power supply.

Ex: 2.2

Equation are $v_3 = A(v_2 - v_1)$;

$$v_{id} = v_2 - v_1, \ v_{icm} = \frac{1}{2}(v_1 + v_2)$$

a)

$$v_1 = v_2 - \frac{v_3}{A} = 0 - \frac{2}{10^3} = -0.02 \text{ V} = -2 \text{ mV}$$

$$v_{id} = v_2 - v_1 = 0 - (-0.002) = +0.002 \text{ V}$$
$$= 2 \text{ mV}$$

$$v_{icm} = \frac{1}{2}(-2\text{mV} + 0) = -1 \text{ mV}$$

b) $-10 = 10^3(5 - v_1) \Rightarrow v_1 = 5.01 \text{ V}$

$$v_{id} = v_2 - v_1 = 5 - 5.01 = 0.01 \text{ V} = 10 \text{ mV}$$

$$v_{icm} = \frac{1}{2}(v_1 + v_2) = \frac{1}{2}(5.01 + 5) = 5.005 \text{ V}$$
$$\simeq 5 \text{ V}$$

c)

$$v_3 = A(v_2 - v_1) = 10^3(0.998 - 1.002) = -4 \text{ V}$$

$$v_{id} = v_2 - v_1 = 0.998 - 1.002 = -4 \text{ mV}$$

$$v_{icm} = \frac{1}{2}(v_1 + v_2) = \frac{1}{2}(1.002 + 0.998) = 1 \text{ V}$$

d)

$$-3.6 = 10^3[v_2 - (-3.6)] = 10^3(v_2 + 3.6)$$

$$\Rightarrow \sqrt{2} = -3.6036 \text{ V}$$

$$v_{id} = v_2 - v_1 = -3.6036 - (-3.6)$$
$$= -0.0036 \text{ V} = -3.6 \text{ mV}$$

$$v_{icm} = \frac{1}{2}(v_1 + v_2) = \frac{1}{2}[-3.6 + (-3.6)]$$
$$= -3.6 \text{ V}$$

Ex: 2.3

From Figure E2.3 we have: $V_3 = \mu V_d$ and

$$V_d = (G_m V_2 - G_m V_1)R = G_m R(V_2 - V_1)$$

Therefore:

$$V_3 = \mu G_m R(V_2 - V_1)$$

That is the open-loop gain of the op amp is $A = \mu G_m R$. For $G_m = 10$ mA/V and $\mu = 100$ we have:

$A = 100 \times 10 \times 10 = 10^4$ V/V Or equivalently 80 dB

Ex: 2.4

The gain and input resistance of the inverting amplifier circuit shown in Figure 2.5 are $-\frac{R_2}{R_1}$ and R_1 respectively. Therefore, we have:

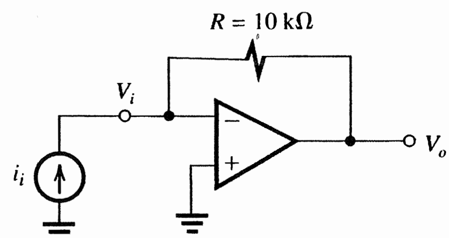
$R_1 = 100$ kΩ and

$$-\frac{R_2}{R_1} = -10 \Rightarrow R_2 = 10 R_1$$

Thus:

$$R_2 = 10 \times 100 \text{ k}\Omega = 1 \text{ M}\Omega$$

Ex: 2.5



From Table 1.1 we have:

$R_m = \left.\frac{V_O}{i_i}\right|_{i_o = 0}$, i.e., output is open circuit

The negative input terminal of the op amp, i.e., V_i is a virtual ground, thus $V_i = 0$

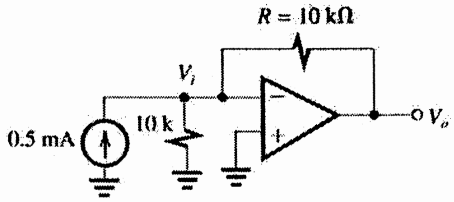
$$V_O = V_i - Ri_i = 0 - Ri_i = -Ri_i$$

$$R_m = \left.\frac{V_O}{i_i}\right|_{i_o = 0} = -\frac{Ri_i}{i_i} = -R \Rightarrow R_m = -R$$
$$= -10 \text{ k}\Omega$$

$R_i = \frac{V_i}{V_i}$ and V_i is a virtual ground ($V_i = 0$),

thus $R_i = \frac{0}{i_i} = 0 \Rightarrow R_i = 0 \ \Omega$

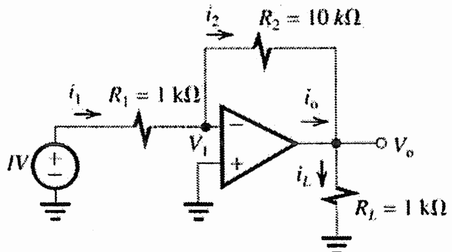
Since we are assuming that the op amp in this transresistance amplifier is ideal, the op amp has zero output resistance and therefore the output resistance of this transresistance amplifier is also zero. That is $R_O = 0 \ \Omega$.



Connecting the signal source shown in Figure E2.5 to the input of this amplifier we have:
V_i is a virtual ground that is $V_i = 0$, thus the current flowing through the 10 kΩ resistor connected between V_i and ground is zero. Therefore

$$V_O = V_i - R \times 0.5 \text{ mA} = 0 - 10 \text{ K} \times 0.5 \text{ mA}$$
$$= -5 \text{ V}$$

Ex: 2.6



V_1 is a virtual ground, thus $V_1 = 0$ V

$$i_1 = \frac{1 \text{ V} - V_1}{R_1} = \frac{1-0}{1 \text{ k}\Omega} = 1 \text{ mA}$$

Assuming an ideal op amp, the current flowing into the negative input terminal of the op amp is zero. Therefore, $i_2 = i_1 \Rightarrow i_2 = 1$ mA

$$V_O = V_1 - i_2 R_2 = 0 - 1 \text{ mA} \times 10 \text{ k}\Omega$$
$$= -10 \text{ V}$$

$$i_L = \frac{V_O}{R_L} = \frac{-10 \text{ V}}{1 \text{ k}\Omega} = -10 \text{ mA}$$

$$i_O = i_L - i_2 = -10 \text{ mA} - 1 \text{ mA} = -11 \text{ mA}$$

$$\text{Voltage gain} = \frac{V_O}{1 \text{ V}} = \frac{-10 \text{ V}}{1 \text{ V}} = -10 \text{ V/V}$$

or 20 dB

$$\text{Current gain} = \frac{i_L}{i_1} = \frac{-10 \text{ mA}}{1 \text{ mA}} = -10 \text{ A/A}$$

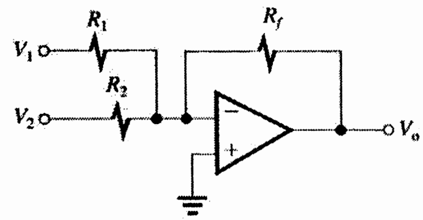
or 20 dB

$$\text{Power gain} = \frac{P_L}{P_i} = \frac{-10(-10 \text{ mA})}{1 \text{ V} \times 1 \text{ mA}} = 100 \text{ W/W}$$

or 20 dB

Note that power gain in dB is $10 \log_{10}\left|\frac{P_L}{P_i}\right|$.

Ex: 2.7



For the circuit shown above we have:

$$V_O = \left(\frac{R_F}{R_1} V_1 + \frac{R_F}{R_2} V_2\right)$$

Since it is required that $V_O = -(V_1 + 5V_2)$.

We want to have:

$$\frac{R_F}{R_1} = 1 \text{ and } \frac{R_F}{R_2} = 5$$

It is also desired that for a maximum output voltage of 10 V the current in the feedback resistor does not exceed 1 mA.

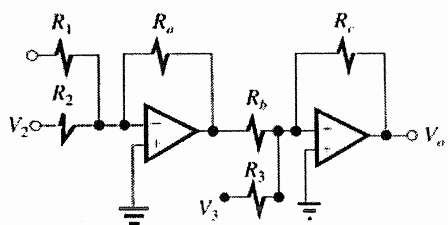
Therefore

$$\frac{10 \text{ V}}{R_f} \le 1 \text{ mA} \Rightarrow R_f \ge \frac{10 \text{ V}}{1 \text{ mA}} \Rightarrow R_f \ge 10 \text{ k}\Omega$$

Let us choose R_f to be 10 kΩ, then

$$R_1 = R_f = 10 \text{ k}\Omega \text{ and } R_2 = \frac{R_f}{5} = 2 \text{ k}\Omega$$

Ex: 2.8



$$V_O = \left(\frac{R_a}{R_1}\right)\left(\frac{R_C}{R_b}\right)V_1 + \left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right)V_2 - \left(\frac{R_C}{R_3}\right)V_3$$

We want to design the circuit such that

$$V_O = 2V_1 + V_2 - 4V_3$$

Thus we need to have

$$\left(\frac{R_a}{R_1}\right)\left(\frac{R_C}{R_b}\right) = 2, \left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right) = 1 \text{ and } \frac{R_c}{R_3} = 4$$

From the above three equations, we have to Find six unknown resistors, therefore, we can arbitrarily choose three of these resistors. Let us choose:

Then we have

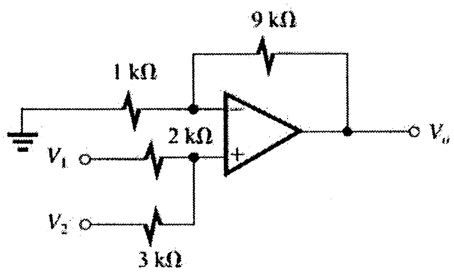
$$R_3 = \frac{R_C}{4} = \frac{10}{4} = 2.5\ \text{k}\Omega$$

$$\left(\frac{R_a}{R_1}\right)\left(\frac{R_C}{R_b}\right) = 2, \Rightarrow \frac{10}{R_1} \times \frac{10}{10} = 2 \Rightarrow R_1 = 5\ \text{k}\Omega$$

$$\left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right) = 1 \Rightarrow \frac{10}{R_2} \times \frac{10}{10} = 1 \Rightarrow R_2 = 10\ \text{k}\Omega$$

Ex: 2.9

Using the super position principle, to find the contribution of v_1 to the output voltage v_0, we set $V_2 = 0$



The V_+ (the voltage at the positive input of the op amp is: $V_+ = \frac{3}{2+3}V_1 = 0.6V_1$

Thus

$$V_O = \left(1 + \frac{9\ \text{k}\Omega}{1\ \text{k}\Omega}\right)V_+ = 10 \times 0.6V_1 = 6\ V_1$$

To find the contribution of V_2 to the output voltage V_0 we set $V_1 = 0$.

Then $V_+ = \frac{2}{2+3}V_2 = 0.4\ V_2$

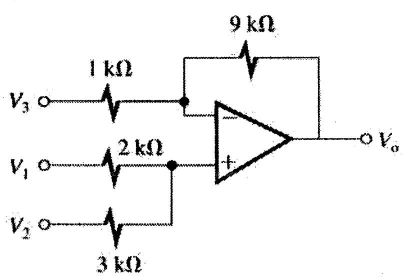
Hence

$$V_O = \left(1 + \frac{9\ \text{k}\Omega}{1\ \text{k}\Omega}\right)V_+ = 10 \times 0.4V_2 = 4V_2$$

Combining the contributions of v1 and v2

To V_O we have $V_O = 6V_1 + 4V_2$

Ex: 2.10



Using the super position principle, to find the contribution of V_1 to V_0 we set $V_2 = V_3 = 0$ Then we have (refer to the solution of exercise 2.9):

$V_O = 6V_1$

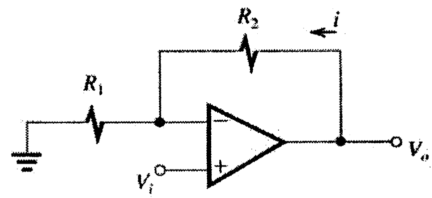
To find the contribution of V_2 to V_0 we set $V_1 = V_3 = 0$, then: $V_O = 4V_2$

To find the contribution of V_3 to V_O we set $V_1 = V_2 = 0$, then

$$V_O = -\frac{9\ \text{k}\Omega}{1\ \text{k}\Omega}V_3 = -9V_3$$

Combining the contributions of V_1, V_2 and V_3 to V_0 we have: $V_O = 6V_1 + 4V_2 - 9V_3$

Ex: 2.11



$$\frac{V_O}{V_i} = 1 + \frac{R_2}{R_1} = 2 \Rightarrow \frac{R_2}{R_1} = 1 \Rightarrow R_1 = R_2$$

If $V_O = 10$ V then it is desired that

$i = 10\ \mu\text{A}$.

Thus,

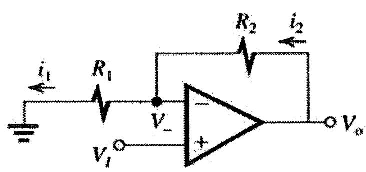
$$i = \frac{10\ \text{V}}{R_1 + R_2} = 10\ \mu\text{A} \Rightarrow R_1 + R_2 = \frac{10\ \text{V}}{10\ \mu\text{A}}$$

$R_1 + R_2 = 1\ \text{M}\Omega$ and

$R_1 = R_2 \Rightarrow R_1 = R_2 = 0.5\ \text{M}\Omega$

Ex: 2.12

a)



$$V_O = A(V_I - V_-) \Rightarrow V_- = V_I - \frac{V_O}{A}$$

$$i_2 = i_1 \Rightarrow \frac{V_O - V_-}{R_2} = \frac{V_-}{R_1} \Rightarrow \frac{V_O}{R_2} = \left(\frac{1}{R_2} + \frac{1}{R_1}\right)V_-$$

$$V_o = \left(1 + \frac{R_L}{R_1}\right)V_- = \left(1 + \frac{R_L}{R_1}\right)\left(V_I - \frac{V_o}{A}\right) \Rightarrow$$

$$V_O + \frac{1 + R_2/R_1}{A}V_O = (1 + R_2/R_1)V_I$$

$$\frac{V_O}{V_I} = \frac{1 + R_2/R_1}{1 + \frac{1 + R_2/R_1}{A}} \Rightarrow G = \frac{1 + R_2/R_1}{1 + \frac{1 + R_2/R_1}{A}}$$