Name ___KEY________
Instructor ______________
Section/College ______________

Electrical Engineering Advancement Exam III

Passing Cutoff XXX/200 = XX

FALL SEMESTER 2020

CLOSED BOOK, CLOSED NOTES
2 HOUR TIME LIMIT

CALCULATORS ARE ALLOWED
(calculators without communication capability only)
ELECTRONIC DEVICES WITH COMMUNICATION CAPABILITY
(electronic devices such as cell phone, pagers, and iPads)
MAY NOT BE USED DURING THE EXAMINATION
(If such devices ring or are visible, a 10% penalty will be given for the first occurrence and exam failure for the second.)

There are 10 problems: please look over the exam to make sure that you have 10 different problems. **Do any eight (8) problems!** Draw a large X through the two problems that you do not want to be graded. If you do not indicate which problems you want to leave out, the first 8 problems will be graded.

Do all work for each problem only on the page supplied for that problem (you may use both sides). **DO NOT**, for instance, continue Problem #3 on the back of Problem #2. Extra blank paper will be supplied if needed. If extra paper is used, show the additional work for each problem on a separate sheet and staple the extra sheet(s) to the appropriate problems.

Question Number	Out of 25 points
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
Total	Passing Cutoff XXX/200

(1)

(a) [5 points] For intrinsic semiconductors at equilibrium, the electron concentration (number of electrons per unit volume) at room temperature is ??? Circle the one correct choice.

Equal to 1.0 x 10^{22} cm^{-3}
Equal to the hole concentration
Equal to 4 electron per atom times the number of atoms per cm^3
None of the above are true

Answer: Equal to the hole concentration

(b) [5 points] Because the energy-gap E_G of crystalline silicon is bigger than that of crystalline germanium, the electron concentration of intrinsic silicon has what relationship to the electron concentration of intrinsic germanium at room temperature? Circle the one correct choice.

$n_{o,Si} > n_{o,Ge}$ $\qquad$ $n_{o,Si} < n_{o,Ge}$ $\qquad$ **Undetermined for given information**

Answer: $n_{o,Si} < n_{o,Ge}$

(c) [5 points] In a pn step junction diode, the electric field inside the depletion region points in which direction (i.e. is positive for which direction)?

From the n region to the p region
From the p region to the n region
Direction depends on bias voltage

Answer: From the n region to the p region

(d) [10 points] Sketch the energy band diagram for a step pn junction for forward bias conditions. Label the edge of the conduction band and the valence band, the Fermi level in both n and p regions, the difference qV_A.

Problem Score
/25

(2)

An abrupt silicon p-n junction has an acceptor concentration 10^{16} cm^{-3} (no donors) in the p-side and a donor concentration 10^{16} cm^{-3} (no acceptors) in the n-side, respectively. The intrinsic carrier concentration of silicon is 1.50 x 10^{10} cm^{-3} at room temperature (300 K). Answer the following questions assuming all dopants are ionized at room temperature.

(a) [7 points] Calculate the potential difference across the junction at equilibrium (i.e. contact potential V_o).

$V_o = (kT/q) \ln [N_{AP,Effective} N_{DN,Effective} / n_i^2) = (0.0259 \text{ V}) \ln[(10^{16} \times 10^{16}/ (1.5 \times 10^{10})^2]$
$V_o = 0.695$ V

V_0 = ____________

(b) [6 points] Calculate the ratio of p-side depletion width x_{po} versus n-side depletion width x_{no} at equilibrium, i.e. x_{po}/x_{no}.

$N_{AP,Effective}\, x_{po} = N_{DN,Effective}\, x_{no}$

$x_{po} / x_{no} = N_{DN,Effective} / N_{AP,Effective} = 1$

x_{po}/x_{no} = ________________

(c) [6 points] Calculate the total potential difference in eV across the junction when a forward bias voltage of V_A = + 0.30 V is applied, i.e. determine the difference between the band edge energy on the p-side of the junction with respect to the n-side.

$qV_o - qV_A = 0.695 - 0.30 = 0.395$ V

(d) [6 points] Calculate the ratio of total depletion width at equilibrium versus total depletion width with a forward bias of V_A = + 0.20 V, i.e. W_o/W.

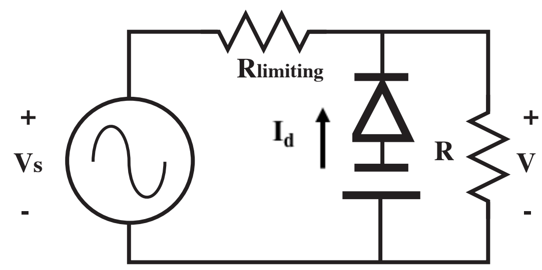
$W_o / W = \sqrt{[V_o / (V_o - V_A)]} = \sqrt{(0.695)/(0.395)]} = 1.326$

W_o/W = ____________________

Problem Score
/25

(3)

Consider an idealized diode with a reverse saturation current 0.01 mA and an abrupt turn-on voltage of 0.70 V (assume no breakdown and operation away from the knee of the diode curve). For the circuit shown, both resistors are 100 Ω, the constant source is V_P = 5.0 V, and the time-dependent source is $V_S = 20 \sin(\omega t)$ V.



(a) [12 Points] State the bias condition of the diode. Calculate the peak positive voltage V and the associated current I_d through the diode. Calculate the answers to at least four significant digits (x.xxxx).

KVL gives $V = - V_P - V_d = - 5 - V_d$ **.**

For $V_S = + 20$ **V, the diode is reverse biased. Hence,**

$I_d = - 0.01$ **mA.**

KCL at the node gives

$$[V - (+20)] / (100\ \Omega) - (- .00001\ \text{A}) + (V) / (100\ \Omega) = 0$$

$$V = (1/2)\,[+ 20 + (- 0.001)]$$

$$V = + 9.9995\ \text{V}$$

V = ________________ **I_d =** ________________

(b) [13 Points] State the bias condition of the diode. Calculate the peak negative voltage V and the associated current I_d through the diode.

KVL gives $V = - V_P - V_d = - 7 - V_d$ **.**

For $V_S = - 20$ **V, the diode is forward biased. Hence,** $V_d = 0.7$ **V.**

Hence, the resistor voltage is at the limit with

$V = - 5 - 0.7 = - 5.7$ **V.**

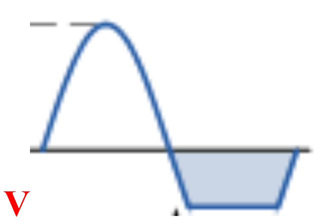
KCL at the node gives

$$[(-5.7\ \text{V}) - (-20\ \text{V})] / (100\ \Omega) - I_d + (- 5.7\ \text{V}) / (100\ \Omega) = 0$$

$$I_d = [2(- 5.7) - (- 20\ \text{V})] / (100\ \Omega)$$

$$I_d = + 0.0860\ \text{A}$$

Sketch (not required in solution) **+9.9995 V**



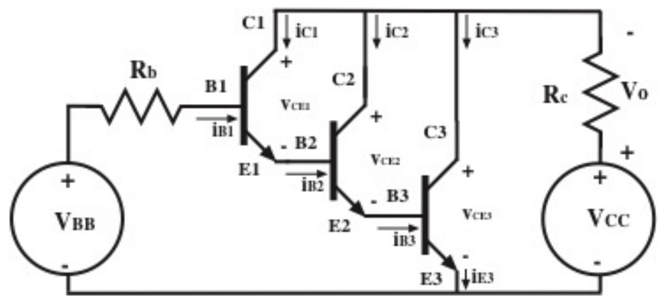
-5.7 V

V = ________________ **I_d =** ________________

Problem Score
/25

(4)

Consider the npn-transistor Darlington amplifier circuit shown with three npn BJTs. The transistors are identical with a nominal beta $\beta = \beta_1 = \beta_2 = \beta_3 = 10$, a turn-on voltage V_{to} = 0.70 V, and a saturation emitter-collector voltage $V_{EC(SAT)}$ = 0.20 V. The circuit values are V_{CC} = 100 V, V_{BB} = 7.1 V, $\boldsymbol{R_{B1}}$ = 10.0 kΩ, and $\boldsymbol{R_C}$ = 10 Ω.



(a) [18 points] Calculate the currents i_{C1}, i_{C2}, and i_{C3}.

KVL Base Side: $-V_{BB} + 3V_{to} + i_{B1} R_{B1} = 0$
$i_{B1} = (1/R_{B1})(V_{BB} - 3V_{to}) = (1/10000)(7.1 - 2.1) = 0.50$ mA

$i_{C1} = \beta\, i_{B1} = (10)(0.50 \text{ mA}) = 5.0$ mA

$i_{C2} = \beta\, i_{B2} = \beta\, i_{E1} = \beta(\beta+1)\, i_{B1} = (10)(11)(0.50 \text{ mA}) = 55.0$ mA

$i_{C3} = \beta\, i_{B3} = \beta\, i_{E2} = \beta(\beta+1)\, i_{B2} = \beta(\beta+1)\, i_{E1} = \beta(\beta+1)(\beta+1)\, i_{B1}$
$i_{C3} = (10)(11)(11)(0.50 \text{ mA}) = 605.0$ mA

i_{C1} = ____________ i_{C2} = ____________ i_{C3} = ____________

(b) [7 points] Calculate the total current through the resistor $\boldsymbol{R_C}$ and the voltage across $\boldsymbol{R_C}$, i.e. i_{CTotal} and V_o.

$i_{CTotal} = i_{C1} + i_{C2} + i_{C3} = 5 \text{ mA} + 55 \text{ mA} + 605 \text{ mA} = 665$ mA

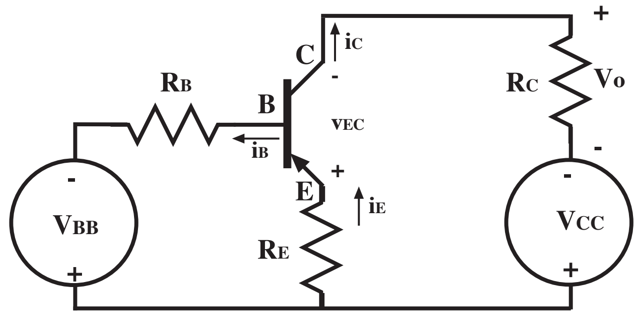
By Ohm's Law: $V_o = i_{CTotal}\, R_{CToal} = (665\text{mA})(0.010\text{ k}\Omega) = 6.65$ V

i_{CTotal} = ____________ V_o = ____________

Problem Score
/25

(5)

Consider the pnp BJT circuit shown with
$\beta = 99$, $V_{to} = 0.7$ V,
$V_{BB} = 5.0$ V, $V_{CC} = 12.0$ V,
$R_B = 12.00$ kΩ, $R_E = 100$ Ω,
and $R_C = 100$ Ω.
The operating transistor voltage $v_{CE} = 12.0$ V. Assume that the circuit is operating in the active region.



(a) [12 points] Calculate the transistor currents i_B and i_E.

Answers:
KVL Base Side:
$- V_{BB} + V_{to} + I_B R_B + I_E R_E = 0$
$- V_{BB} + V_{to} + I_B R_B + I_B (1 + \beta) R_E = 0$

$i_B = (V_{BB} - 3V_{to}) / [(1 + \beta) R_E + R_B] = (5.0 – 0.7) / [(1 + 99) 100 + 12000] = 0.1955$ mA

$i_E = \beta i_B = (1 + 99) (0.1955$ mA$) = 19.55$ mA

KVL LL gives
$- V_{CC} + v_{ce} + i_E R_e = 0$
$i_E = (1/R_e)(V_{CC} – v_{ce}) = (1/1000)(21 - 12)$
$i_E = 9$ mA

$i_B = [1/(\beta + 1)]\ i_E = (1/200)(0.009) = 0.000045$ A $= 0.045$ mA

$i_C = [\beta/(\beta + 1)]\ i_E = (199/200)(0.009) = 0.008955$ A $= 8.955$ mA

$i_B =$ ____________ $i_E =$ ____________

(b) [13 points] Calculate the operating point i_C *and* v_{EC}.

Answer:
$i_C = \beta i_B = (99) (0.1955$ mA$) = 19.35$ mA

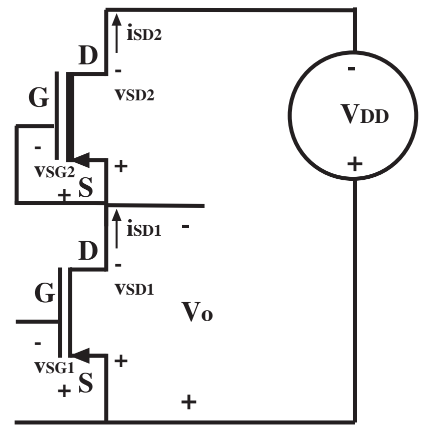
Load-Line Collector-side KVL
$- V_{CC} + i_E R_E + i_C R_C + v_{EC} = 0$
$v_{EC} = + V_{CC} - i_E R_E - i_C R_C = + V_{CC} – i_C [(\beta + 1)/\beta] R_E - i_C R_C +$
$v_{EC} = (12) - (19.55$ mA$)[(100/99) (100) + 100] = 8.11$ V

$i_C =$ ____________ $v_{EC} =$ ____________

Problem Score
/25

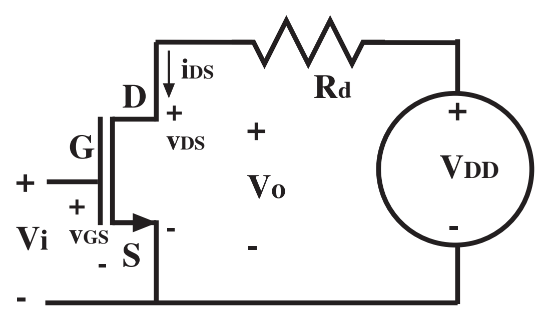
(6)

(a) [5 points] For the inverter MOSFET circuit shown, the enhancement-mode p-channel MOSFET has parameters V_{on} and K and the depletion-mode p-channel MOSFET has parameters V_{po} and I_{SDS}. For the upper or load MOSFET, sketch the IV characteristic i_{SD2} vs. v_{SD2}. State the control voltage v_{SG2} value and label the axes and any key voltage or current values.



(b) [5 points] For the inverter MOSFET circuit shown in part a, the enhancement-mode p-channel MOSFET has parameters V_{on} and K and the depletion-mode p-channel MOSFET has parameters V_{po} and I_{SDS}. Sketch the **load line** for the lower or driver transistor i_{SD1} vs. v_{SD1}. Label the axes and important intercept values.

(c) [9 points] Consider an n-channel MOSFET circuit with V_{on} = 3.00 V, K = 1.00 mA/V^2, $\boldsymbol{R_d}$ = 1.00 kΩ, V_{DD} = 20.0 V, and V_i = 5.0 V. Calculate the operating point or Q-point, i.e. i_{DS} and v_{DS}.



Note that $v_{GS} = V_i$.
Assume saturation.
$i_{DS} = KV_{on}^2[(v_{GS}/V_{on}) - 1]^2$ = (1.0 mA/V^2) (3)^2 [(5/3) – 1]^2 = 4.0 mA

The KVL load line gives $v_{DS} = V_{DD} – i_{DS} R_d$ = 20 – (0.004) (1000) = 16 V
Check: $v_{DS} - v_{GS} \geq - V_{on}$ or 16 - 5 = 11 $\geq$ - 3. Saturation confirmed

Answers: v_{DS} = 16 V and i_{DS} = 4.0 mA

v_{DS} = ____________________ i_{DS} = ____________________

(d) [6 points] For the MOSFET circuit in part b with V_{on} = 3.00 V, K = 1.00 mA/V^2, V_{DD} = 20.0 V, and V_i = 5.0 V, calculate the range of $\boldsymbol{R_d}$ for which the transistor operation stays in saturation.

Saturation must satisfy $v_{DS} - v_{GS} \geq - V_{on}$ or $v_{DS} \geq + v_{GS} - V_{on}$
The threshold of saturation occurs for $v_{DS} = v_{GS} - V_{on}$ or v_{DS} = 5 - 3 = + 2V
The saturation current for V_i = 5.0 V is

$i_{DS} = KV_{on}^2[(v_{GS}/V_{on}) - 1]^2$ = (1.0 mA/V^2) (3)^2 [(5/3) – 1]^2 = 4.0 mA

By KVL, the threshold value for resistance is

$- V_{DD} + v_{DS} + i_{DS} R_d = 0$ or $R_d = (+ V_{DD} - v_{DS}) / i_{DS}$ = (20 - 2) / (0.004) = 4.50 kΩ.

The range is then

$R_d \leq$ 4.50 kΩ

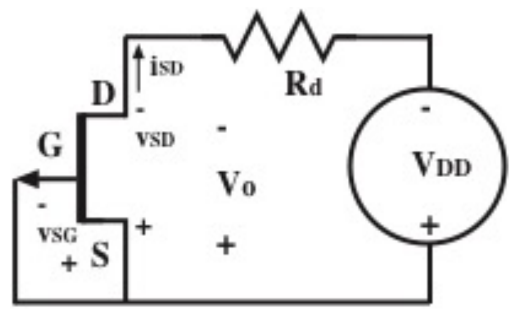
Range of R_d: ____________________

Problem Score
/25

(7)

(a) [5 points] Consider a p-channel JFET with specifications V_{po} and I_{SDS}. Sketch the saturation curve i_{SD} vs. v_{SG} i.e. the curve for saturation conditions. Label all intercepts.

(b) [20 points] Consider the p-channel JFET circuit shown. The transistor parameters/specifications are V_{po} = 4.00 V and I_{SDS} = 10.0 mA. The circuit values are R_d = 1.70 kΩ and V_{DD} = 20.0 V. Calculate the input voltage v_{SG}; the operating point or Q-point, i.e. i_{SD} and v_{SD}; and the load-line intercepts for current and voltage. Sketch the current-voltage characteristic and the load-line on the same graph. Label the operating point (Q-point) and the load-line intercepts.



Note that $v_{SG} = 0$
Assume saturation.
$i_{SD} = I_{SDS}[1 + (v_{SG}/V_{on})]^2$ = (10.0 mA)$[1 + 0]^2$ = 10.0 mA
The KVL load line gives $v_{SD} = V_{DD} - i_{SD} R_d$ = 20 – (0.010) (1700) = 3 V
Check: Is $v_{SD} - v_{SG} \geq V_{po}$? 3 - 0 = 3 $\leq$ 4. Unsaturated Conditions

Simultaneous solution needed for LL and i_{SD} unsaturated equation
$i_{SD} = I_{SDS}\{2[1 + (v_{SG}/V_{po})]^2 (v_{SD}/V_{po}) - (v_{SD}/V_{po})^2\}$ = = $(V_{DD} - v_{SD})/R_d$
0.01$[2(1 + 0)(v_{SD}/4) - (v_{SD}/4)^2]$ = $(20 - v_{SD})/1700$
1.0625(v_{SD}^2) – 9.5(v_{SD}) + 20 = 0 gives v_{SD} = 9.5488 V, 3.3923 V
v_{SD} = 3.3923 V 3.3923 is in the correct range
Then, $i_{SD} = (V_{DD} - v_{SD})/R_d$ = (20 – 3.3923)/1700 = 9.769 mA

Answers: v_{SD} = 3.3923 V and i_{SD} = 9.769 mA

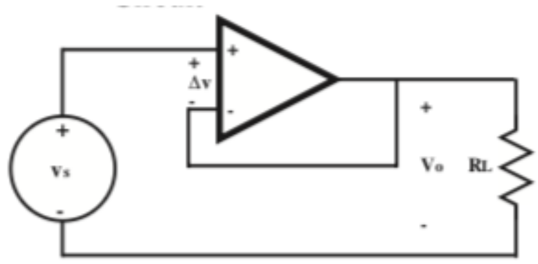
v_{SG} =______________ v_{SD} =______________ i_{SD} =______________

Voltage-axis intercept = (____, 0 A) **Current-axis intercept = (0 V, _____)**

Problem Score
/25

(8)

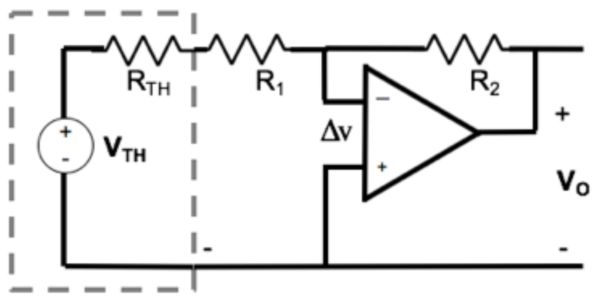
(a) [8 points] The OpAmp shown has ideal resistances R_{in} and R_{out} and has a finite open-loop gain A = 20,000. For the circuit shown, calculate V_O/V_S. Express the answer to at least 5 significant digits (x.xxxxx).



KVL: $-V_S + \Delta v + V_O = 0$ and $A\,\Delta v = V_O$
$-V_S + V_O/A + V_O = 0$
$V_O/V_S = 1/[(1/A) + 1] = 1/[(1/20000) + 1] = 0.99995$

V_O/V_S = ______________________________

(b) [7 points] For the OpAmp circuit shown, sketch the equivalent circuit in which the OpAmp is replaced with appropriate circuit elements. Assume **non-ideal** OpAmp parameters.



(c) [3 points] What type of OpAmp circuit is shown in part b? (Circle the best choice.)

Inverting (V_O / V_{TH} neg.) **Non-Inverting (V_O / V_{TH} pos.)** **Answer: Invert.**

(d) [7 points] Use the OpAmp circuit shown in part b and assume **ideal** parameters. Consider the OpAmp circuit shown. The OpAmp is ideal. The Thevenin circuit values are

V_{TH} = 5.00 V and R_{TH} = 1.00 kΩ.

The feedback resistor R_2 = 20.00 kΩ. Calculate the value of resistor R_1 such that the magnitude of the output voltage to the Thevenin voltage is $|V_O/V_{TH}| = 5$.

KCL for the (-) terminal:
(OpAmp input current is zero and feedback drives Δv to zero)

$(0 - v_{TH})/(R_1 + R_{TH}) + (0 - v_o)/R_2 = 0$

Hence,

$V_O/V_{TH} = [-R_2/(R_1 + R_{TH})]$
$|V_O/V_{TH}| = 5 = [R_2/(R_1 + R_{TH})] = [20000/(R_1 + 1000)]$
R_1 = 3000 Ohms

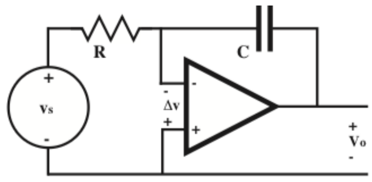
R_1 = ______________________________

Problem Score
/25

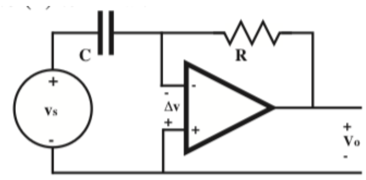
(9)

(a) [8 points] Identify the two OpAmp circuits shown. (Select the best answers.)

Circuit A:



Circuit B:



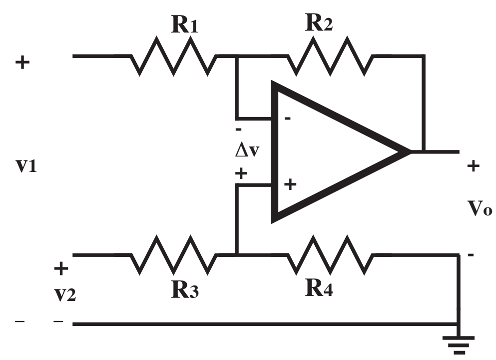
Differentiating B and Integrating A

Circuit _______ is a Differentiating circuit ($V_o = -RC\, d(V_s)/dt$)
Circuit _______ is a Integrating ($V_o = (-1/RC) \int(V_s)d\tau$

(b) [8 points] Consider the OpAmp circuit shown. Assume an **ideal** OpAmp. The resistance values are

$R_1 = 1.00$ kΩ, $R_2 = 5.00$ kΩ,
$R_3 = 2.00$ kΩ, and $R_4 = 2.00$ kΩ.

Operation is in the linear range.



Calculate the output V_O as a function of v_1 when $v_2 = 0$. Hint: Use superposition.

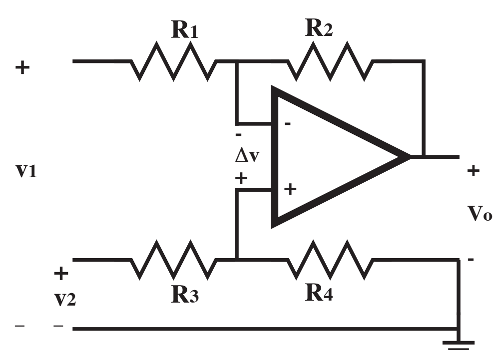
No current in R_3 and R_4 so $V_+ = 0$. $\Delta v = 0$ due to negative feedback.
KCL at (-) terminal with $V_- = 0$ gives $(0 - v_1)/(R_1) + (0 - V_o)/R_2 = 0$
$V_o = (R_2/R_1)v_1$ (inverting case)

$Vo\,|_{v2=0} = Vo_1 =$ (________________________________) v_1

(c) [9 points] Consider the same OpAmp circuit. Assume an **ideal** OpAmp. The resistance values are the same as in (b) and are

$R_1 = 1.00$ kΩ, $R_2 = 5.00$ kΩ,
$R_3 = 2.00$ kΩ, and $R_4 = 2.00$ kΩ.

Operation is in the linear range.



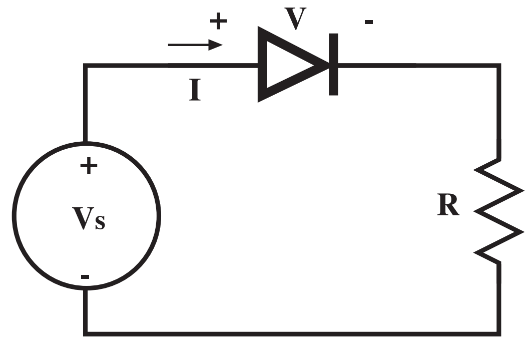
Calculate the output V_O as a function of v_2 when $v_1 = 0$. Hint: Use superposition.

By voltage division (no current into ideal OpAmp) $V_+ = [(R_4)/(R_3 + R_4)]v_2$
$V_+ = V_-$ since $\Delta v = 0$ (negative feedback).
By voltage division (no current into ideal OpAmp) $V_- = [(R_1)/(R_1 + R_2)]V_o$
$V_o = [(R_1 + R_2)/R_1)]V_- = [(R_1 + R_2)/R_1)]\ [(R_4)/(R_3 + R_4)]v_2$

$Vo\,|_{v1=0} = Vo_2 =$ (________________________________) v_2

Problem Score
/25

(10)



Consider the Si pin photodiode circuit shown with source voltage V_S and resistance $\boldsymbol{R}$ = 6000 Ohms. The bandgap energy for Si is E_G = 1.12 eV. The reverse saturation current (for "dark" conditions) is 0.10 mA. Light of wavelength λ = 0.900 μm is incident; the efficiency is 0.90. Assume the photodiode voltage $|V| >> kT/q$ and room temperature.

(a) [5 points] For photoconductive operation as described in the lecture notes, what is the correct bias condition for the photodiode? Choose (circle) the correct choice.

Forward bias **No Bias** **Reverse Bias**

Answer: Reverse Bias.

(b) [5 points] Calculate the photon energy E_P for this wavelength. Express the photon energy in eV.

Answer:

$E_P = hc/\lambda = (4.136 \times 10^{-15}$ eV-s$)(2.998 \times 10^{10}$ cm/s$)/(0.9 \times 10^{-4}$ cm$) = 1.851 \times 10^{-4}$ eV

E_P = 1.378 eV

E_P = ________________

(c) [10 points] For an absorbed optical power P at this wavelength λ = 0.900 μm, the photo-induced current is I_{light} = 1.0 mA. Calculate the absorbed optical power in W.

Answer:

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

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

$P = [(0.001$ C/s$)(6.626 \times 10^{-34}$ J-s$)(2.998 \times 10^{10}$ cm/s$)]/[(0.9)(1.602 \times 10^{-19}$ C$)(0.00009$ cm$)]$

P = 1.53 mW

P= ________________

(d) [5 points] For the photo-induced current of I_{light} = 1.0 mA, the operating voltage is V = - 7.50 V. Calculate the needed source voltage V_S.

Answer:

$I = - I_o - I_{light}$ = -(o.1 mA) - 1.0 mA = - 1.1 mA

KVL LL gives $- V_S + V + I R = 0$

$V_S = V + I R$ = (- 7.5 V) + (- 1.1 mA) (6000 Ohms) = - 14.1 V

V_S = ________________

Problem Score
/25