**MASSACHUSETTS INSTITUTE OF TECHNOLOGY**

Department of Electrical Engineering and Computer Science

# 6.301 Solid State Circuits

**Final Exam**

December 15, 2008

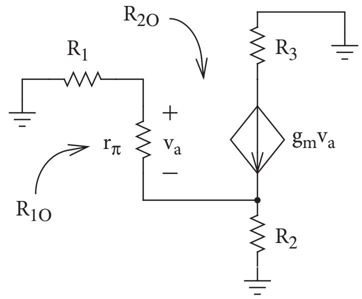
180 minutes

Room 4-145

1. This examination consists of four problems. Work all problems.
2. This examination is closed book.
3. Please summarize your solutions in the spaces provide in this examination packet. Draw all sketches neatly and clearly where requested. Remember to label ALL important features of any sketches.
4. All problems have equal weight.
5. Make sure that your name is on this packet and on each examination booklet.

Good luck.

General equations, worst case OCT:

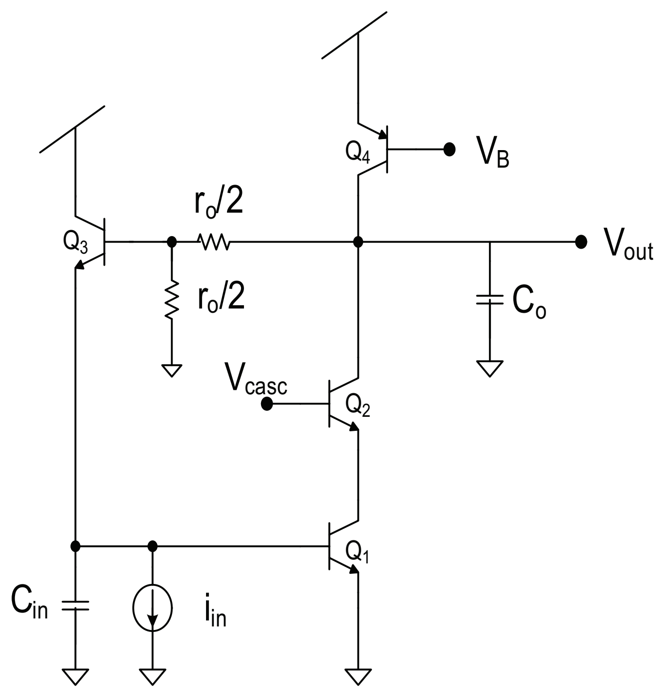



$$R_{10} = r_\pi \left\| \frac{(R_1 + R_2)}{1 + g_m R_2} \right.$$

$$R_{20} = \underbrace{R_1 \| [r_\pi + (\beta + 1) R_2]}_{R_\|} + R_3 + \frac{g_m r_\pi R_\| R_3}{r_\pi + (\beta+1) R_2}$$

**Problem 1 OCT's and transfer functions**

Consider the following amplifier:




- $\beta \to \infty$
- $C_\pi = 0$
- $C_\mu = 100\text{fF}$
- $C_o = C_{in} = 1\text{pF}$
- Assume $I_{c1} = I_{c2} = I_{c3} = I_{c4}$
- Do not ignore the Early effect.

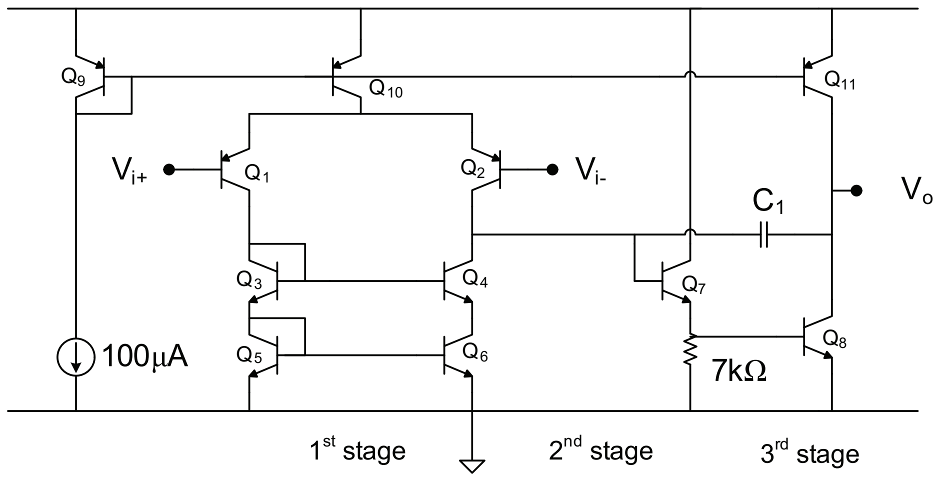
**(a)** Solve for the following transfer functions

- $\frac{v_{out}}{i_{in}}$
- $\frac{v_f}{v_{out}}$
- $v_{in}(v_f, i_{in})$

**(b)** Approximate the 3dB frequency ($f_{3dB}$) using the method of open circuit time constants. Make reasonable approximations.

**Problem 2 Op amps**

A three-stage BJT op-amp is shown below. Assume $V_{BE,on} = 0.7\text{V}$, $\beta = 100$, $V_A = 2.5\text{V}$, $\frac{kT}{q} = 25\text{mV}$.




**(a)** Calculate all collector currents

**(b)** Calculate the low-frequency gain of each stage. Include $r_\pi$'s and $r_o$'s in your calculation.

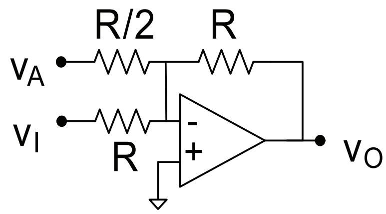
**(c)** Explain the function of the 2nd stage.

**(d)** The dynamics of the amplifier are dominated by $C_1$. Estimate the location of the lowest frequency pole in terms of $C_1$ and quantities involved in part (b).

**Problem 3 Op Amp applications**

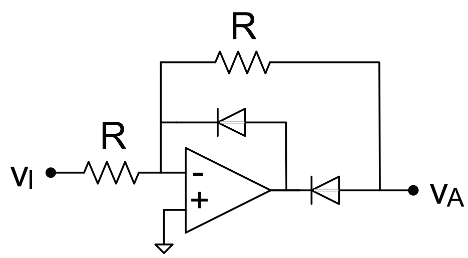
Note: For parts (a) and (b) you may assume the op amps and diodes are ideal.

**(a)** Derive the voltage $v_o$ as a function of $v_I$ and $v_A$ in the following circuit

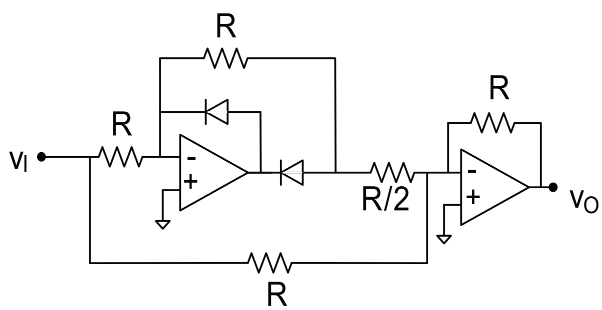



**(b)** Derive $v_A$ as a function of $v_I$ in the following circuit when:

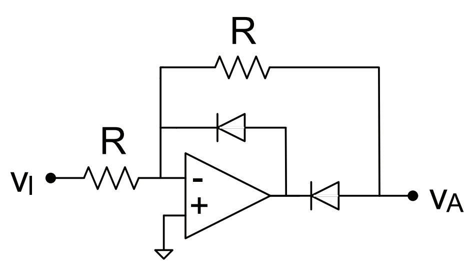
1. $v_I > 0$
2. $v_I < 0$




**(c)** What function is implemented by the following circuit? Give both a qualitative and quantitative ($\frac{v_o}{v_I}$) answer.

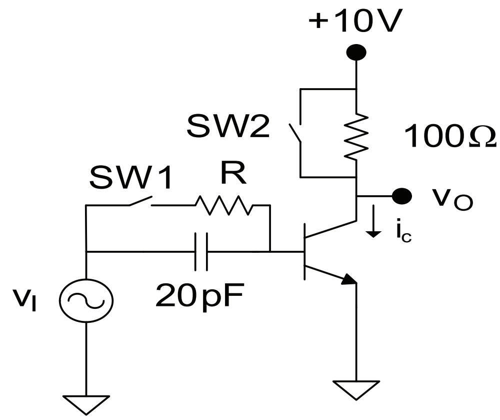



**(d)** Now consider the diodes to be nonideal (i.e., they have a forward drop of 0.6V when conducting). What is the output voltage $v_A$ of the circuit in part (b) under this condition?



**Problem 4 Charge Control**

An inverter circuit is shown below




The transistor has negligible space-charge layer capacitances. In this case, the charge control equations are

$$
\begin{aligned}
i_C &= \frac{q_F}{\tau_F} - q_R\left(\frac{1}{\tau_R} + \frac{1}{\tau_{BR}}\right) - \frac{dq_R}{dt} \\
i_B &= \frac{q_F}{\tau_{BF}} + \frac{dq_F}{dt} + \frac{q_R}{\tau_{BR}} + \frac{dq_R}{dt} \\
i_E &= \frac{q_F}{\tau_{BF}} - q_F\left(\frac{1}{\tau_F} + \frac{1}{\tau_{BF}}\right) - \frac{dq_F}{dt}
\end{aligned}
$$

When the transistor is in saturation

$$i_B - i_{Bo} = \frac{q_S}{\tau_S} + \frac{dq_S}{dt}$$

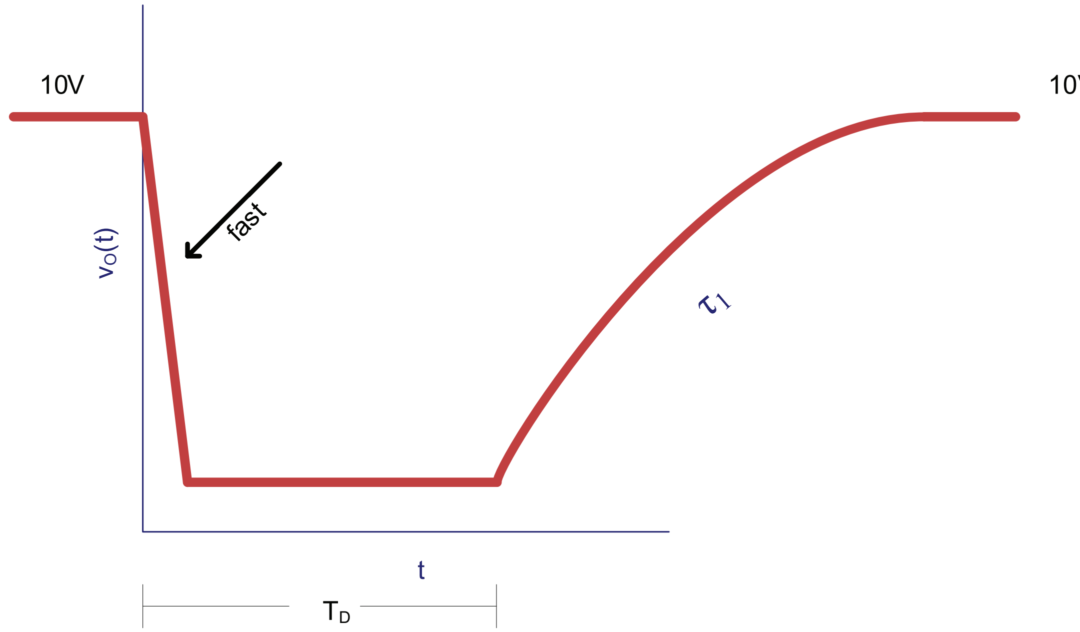
The transistor parameters are

| | | | |
|---|---|---|---|
| $\tau_F = 1$ns | $\beta_F = 100$ | $\tau_{BF} = 100$ns | $\tau_S = 15.1$ns |
| $\tau_R = 2$ns | $\beta_R = 5$ | $\tau_{BR} = 10$ns | |

**(a)** The circuit is initially configured with switch 1 open and switch 2 closed. Input voltage $v_I(t)$ is a 10.7 volt step and the initial value of the capacitor voltage is zero. Find $i_C(t)$ valid for all time slightly greater than zero.

**(b)** Switch 1 is now closed. Other conditions remain the same as for part (a). Find the value of $R$ that makes $i_C$ a constant for all time slightly greater than zero.

**(c)** Switches 1 and 2 are now both opened. With $v_I(t)$ a 10.7V step and zero initial capacitor voltage, the voltage $v_o(t)$ is given by the following graph




What are the values of delay time $T_D$ and $\tau_1$? You may express $T_D$ in terms of logarithms if you wish.

**(d)** The circuit is now operated with switch 1 closed and switch 2 open, $R = 2.5\text{k}\Omega$, and $v_I$ a constant 10.7 volts. After equilibrium is reached switch 2 is closed. What is the value of $i_C$ slightly after the switch is closed? What is the final value of $i_C$?