Mid-term exam, Electronic Circuits, Spring semester, 2018

April 16, 2018

We have 50 questions. The exam ends at AM 10:40. Write down your answers on the answer sheets. Explicitly show the unit of your answer. For each question, use the designated answer slot.

In the mid-term exam, no partial credit will be given.

When the numbers are provided, just answer a numerical value and a correct unit.

If not stated otherwise, use the long-channel IV characteristics of MOSFETs.

If not stated otherwise, include the output resistance in the small-signal MOSFET model.

Some useful facts are summarized below:

For a resistor, $V = IR$. For a capacitor, $I = C\, dV/dt$. For an inductor, $V = L\, dI/dt$.

A good value for the thermal voltage, V_T, at room temperature is 0.02585 V. You may use an approximate value.

Approximately, $\ln 10 \approx 2.3$. Moreover, $e^{-0.7} \approx 0.5$.

The vacuum permittivity is approximately $8.85 \times 10^{-12}\ \mathrm{F/m}$.

The (absolute) elementary charge is approximately $1.6 \times 10^{-19}\ \mathrm{C}$.

At a given time, the power dissipation is defined by $P(t) = I(t)V(t)$.

At room temperature, the intrinsic carrier density of silicon, n_i, is 10^{10} /cm^3.

The built-in potential in a pn junction is given by $V_0 = V_T \ln \frac{N_A N_D}{n_i^2}$.

1. Consider a resistor. Its resistance is $1.5\ \mathrm{k\Omega}$. The voltage, $3.25\sin(10^6 t)$ (V), is applied. Calculate the resistor current.

2. Consider a capacitor. Its capacitance is $1\ \mathrm{nF}$. The voltage, $3.25\sin(10^6 t)$ (V), is applied. Calculate the capacitor current.

3. Consider the circuit shown in Fig. P3. Calculate the current, I_{ans}.

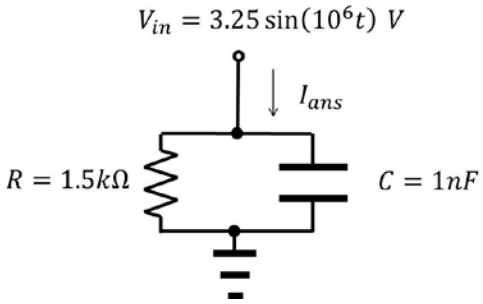

Fig. P3.

4. Consider the circuit shown in Fig. P4. Calculate the current, I_{ans}.

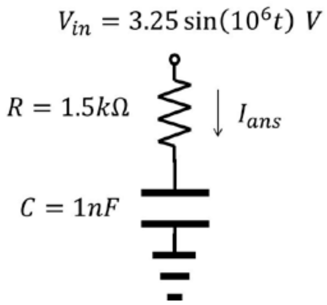

Fig. P4.

5. Calculate the impedance (the resistance in this problem) seen from the "in" node..

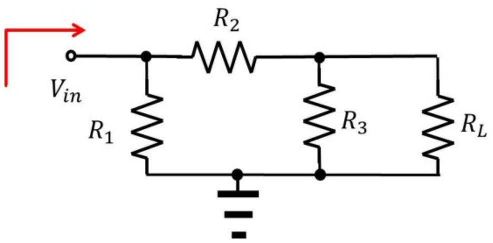

Fig. P5.

6. For a circuit shown in Fig. P5, V_{in} is 1 V. Moreover, R_1, R_2, and R_3 are fixed. Only the resistance of R_L can be changed. Then, write down the maximum possible voltage across R_L.

7. Calculate the impedance (the resistance in this problem) seen from the "out" node..

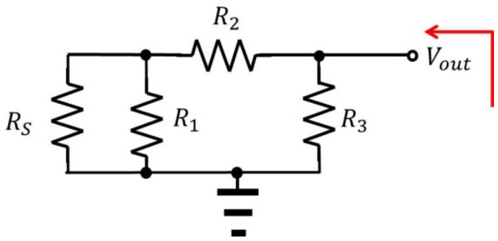

Fig. P7.

8. In a pn diode, two different regions in the silicon (Si) substrate can be found. Let us call me the regions X and Y. In the region X, impurity atoms such as boron (B) are found. In the region Y, impurity atoms such as phosphorus (P) or arsenic (As) are found. Which region is acting as the anode? X or Y?

9. For a diode, the terminal current and the terminal voltage are related by $I = I_S\left(\exp(\frac{V}{V_T}) - 1\right)$. Express $\frac{dI}{dV}$ using only $(I + I_S)$ and V_T.

10. Consider a diode with the reverse saturation current of 1 fA. Its diode current is 1 mA. Estimate the small-signal resistance seen from the anode. Assume the low-frequency limit.

11. Consider two diodes. For a diode, $I = I_S\left(\exp(\frac{V}{V_T}) - 1\right)$. For the other one, due to many defects inside the diode, $I = I_S\left(\exp(\frac{V}{2V_T}) - 1\right)$. In this problem, the reverse saturation currents of two diodes are identical. When the applied anode voltage is 0.60 V, estimate the ratio between two diode currents. Assume the room temperature.

12. Consider the circuit shown Fig. P12. The diode conducts 30 pA, when the diode voltage is 0.3 V. The output voltage is 0.3 V. Calculate the value of V_{bat}.

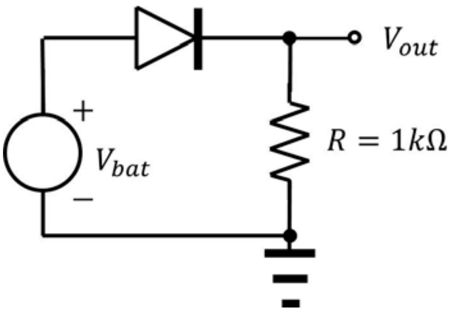

Fig. P12.

13. Consider the circuit shown in Fig. P12, again. In this problem, the value of V_{bat} is -1 V.

Calculate the output voltage.

14. Consider the circuit shown in Fig. P14. Two diodes (D1 and D2) have different reverse saturation currents, I_S and $10^2 I_S$, respectively. The diode with I_S (D1) conducts 30 pA, when the diode voltage is 0.3 V. Estimate the output voltage. The voltage of the battery is 0.9 V

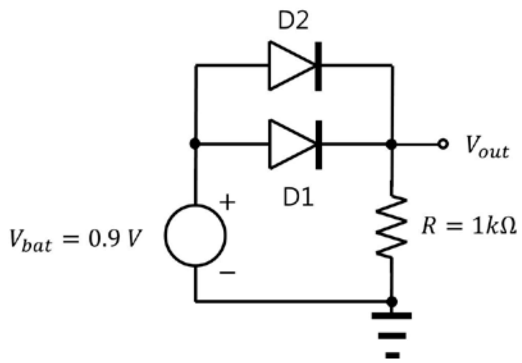

Fig. P14.

15. Consider the circuit shown in Fig. P15. The same diodes used in P14 are used. Estimate the output voltage.

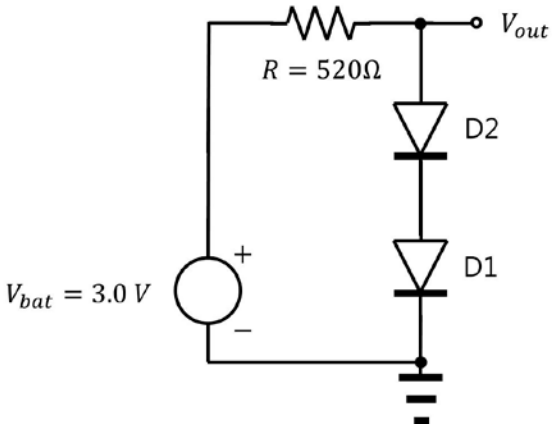

Fig. P15.

16. Consider a planar MOSFET. Its channel length (L) is 20 nm and its channel width (W) is also 20 nm. It has a silicon dioxide (SiO2) layer whose thickness is 2 nm. Calculate the oxide capacitance (which is equal to $C_{ox}WL$). Remember that the vacuum permittivity is approximately $8.85 \times 10^{-12}\ \mathrm{F/m}$. The relative permittivity of the silicon dioxide is 3.9.

17. Instead of the silicon dioxide with 2 nm thickness, a hafnium oxide (HfO2) layer is used. The relative permittivity of the hafnium oxide is 25. Calculate the thickness of the hafnium oxide layer to have the same capacitance value in the last problem.

18. In the lecture, we have studied about the threshold behavior of the Metal-Oxide-Semiconductor (MOS) structure. When the density of the p-type dopant atoms (such as boron) is increased, what happens to the threshold voltage? Is the threshold voltage increased, decreased, or doesn't change?

19. For a MOS structure, the oxide capacitance is 0.4 fF. The threshold voltage of this MOS structure is 0.3 V. Calculate the number of electrons at the gate voltage of 0.7 V.

20. The threshold voltage of a NMOSFET is 0.3 V. Moreover, $\mu_n C_{ox}\frac{W}{L}$ is $4\ \mathrm{mA/V^2}$. Assuming the long-channel MOSFET, calculate the saturation current for the gate voltage of 0.7 V.

21. The threshold voltage of a NMOSFET is 0.3 V. Again, $\mu_n C_{ox}\frac{W}{L}$ is $4\ \mathrm{mA/V^2}$. Assuming the long-channel MOSFET, calculate the transconductance at $V_G = V_D = 0.7\,V$.

22. The threshold voltage of a NMOSFET is 0.3 V. Moreover, $\mu_n C_{ox}\frac{W}{L}$ is $4\ \mathrm{mA/V^2}$. Assuming the long-channel MOSFET, calculate the transconductance at $V_G = 0.7\,V$ and $V_D = 0.1\,V$.

23. In a realistic model, the drain current of a MOSFET in the saturation mode is described as

$$I_D = \frac{\mu_n C_{ox} W (V_{GS} - V_{TH})^2}{2L}(1 + \lambda V_{DS}),$$

where all parameters except for V_{GS} and V_{DS} are assumed to be constant. Using this model, express the transconductance. V_{DS} cannot be used in your answer.

24. Consider the same model in the last problem. Explicitly show the output resistance. Again, V_{DS} cannot be used in your answer.

25. Consider the circuit shown in Fig. P25. The threshold voltage of the MOSFET is 0.8 V. When the gate voltage is lower than the threshold voltage, calculate the output voltage.

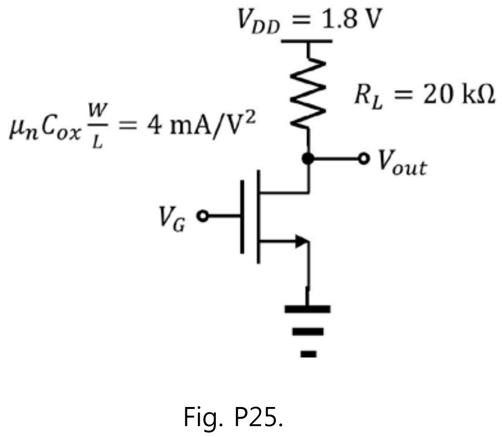

Fig. P25.

26. Consider the same circuit shown in Fig. P25. At a certain gate voltage, the MOSFET is at the boundary between the triode mode and the saturation mode. Calculate such a gate voltage. Write your answer in the mV scale.

27. Consider the same circuit shown in Fig. P25. When the gate voltage is 1.8 V, calculate the output voltage. Write your answer in the mV scale.

28. Consider the same circuit shown in Fig. P25. At a certain gate voltage, the output voltage (the drain voltage) is identical to the gate voltage. Calculate such a gate voltage. Write your answer in the mV scale.

29. From P25 to P28, we have calculated various (V_G,V_{out}) values. The gate voltage is used as an input voltage and the drain voltage is used as an output voltage. Using these values, the circuit shown in Fig. P25 can be interpreted as a logic gate. Which logic gate is it?

30. Consider the circuit shown in Fig. P30. All MOSFETs have a common threshold voltage, 0.8 V. Moreover, for every MOSFET, $\mu_n C_{ox}\frac{W}{L}$ is $4\ \mathrm{mA/V^2}$. When the gate voltage is 0 V, calculate the output voltage.

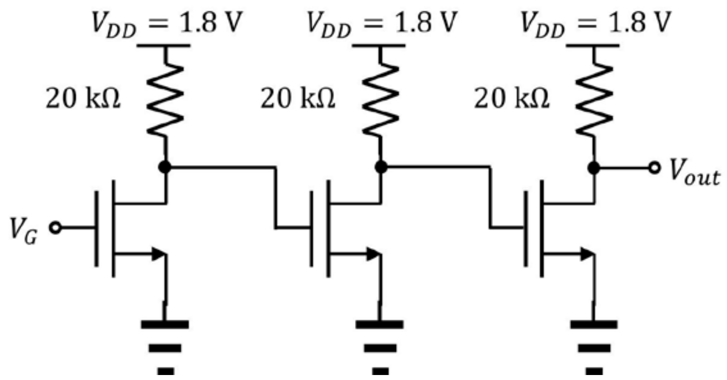

Fig. P30.

31. Consider the circuit shown in Fig. P31. The threshold voltage of the MOSFET is fixed to 0.8 V. What is the maximum source voltage to allow the conduction?

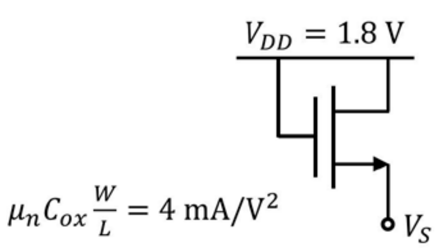

Fig. P31.

32. Consider the same circuit shown in Fig. P31. The source voltage is lower than the answer of the last question. Using the value of the source voltage (in the V scale), express the drain current.

33. Consider the same circuit shown in Fig. P31. The time-varying source voltage is given as $V_S(t) = 0.8 + 0.1\sin(10t)$. Express the drain current as a function of time. Use only constants and sinusoidal functions. Avoid the power of sinusoidal functions.

34. Consider the circuit shown in Fig. P34. Two MOSFETs in the circuit have the identical parameters. Even the threshold voltages are assumed to be the same, 0.8 V. When the gate voltage is 1.1 V, what is the output voltage?

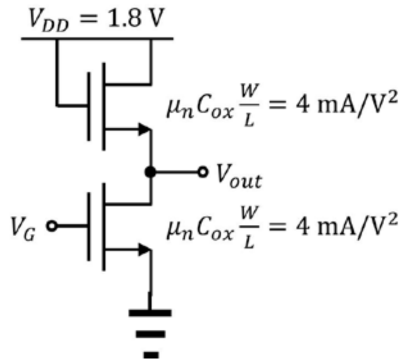

Fig. P34.

35. Consider a current source. It has two terminals. Draw its small-signal model.

36. Consider a voltage source. It has two terminals. Draw its small-signal model.

37. Consider an N-MOSFET. (The MOSFET covered in the lecture is the N-MOSFET.) Assume that the MOSFET is properly biased. Draw its small-signal model.

38. Assume the low-frequency limit. Write down the small-signal gate resistance. The source and drain are ac-grounded.

39. Assume the low-frequency limit. Write down the small-signal drain resistance. The source and gate are ac-grounded.

40. Assume the low-frequency limit. Write down the small-signal source resistance. The gate and drain are ac-grounded.

41. Assume the low-frequency limit. Write down the small-signal drain resistance. Although the gate is ac-grounded, the source is terminated by a source resistor, R_S.

42. Assume the low-frequency limit. Write down the small-signal source resistance. Although the gate is ac-grounded, the drain is terminated by a drain resistor, R_D.

43. Consider the circuit shown in Fig. P43. Draw its small-signal model.

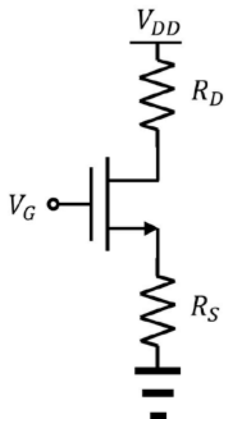

Fig. P43.

44. Complex number representations that denote sinusoidal signals at a fixed frequency are called phasors. In this problem, for a given time-varying function $f(t)$, let us denote its phasor $f(\omega)$. Then, $f(t) = Re[f(\omega)\exp(j\omega t)]$. For example, when $f(t) = \cos\omega t$, its phasor is 1. When $f(t) = \sin\omega t$, its phasor is $-j$. Consider a phasor, $3 + j4$. Write down the time-varying function for the phasor.

45. The impedance (Z) satisfies a relation, $V(\omega) = Z\,I(\omega)$. For a capacitor, $I(t) = C\,dV(t)/dt$. Write down the capacitor impedance.

46. For an inductor, $V(t) = L\,dI(t)/dt$. Write down the inductor impedance.

47. Calculate the node voltage.

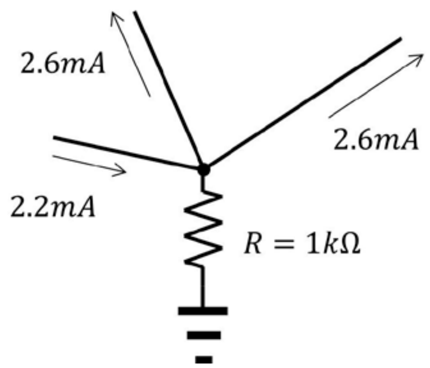

Fig. P47.

48. A netlist file is shown below. Draw its circuit schematic.

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v1 batt 0 1.5

r1 batt x 1000

r2 x y 2000

r3 y 0 2k

r4 y 0 3k
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49. Consider the same circuit in the last problem. Calculate the current of the terminal #1 in the r1. Write your answer in the μA scale.

50. Consider a resistor. Its resistance is $10\,\Omega$. Its terminal current follows Ohm's law. In this problem, we want to express Ohm's law using a scalar product of two vectors. Write down the appropriate values of a_1, a_2, a_3, a_4, and b.

$$\begin{bmatrix} a_1 & a_2 & a_3 & a_4 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ V_1 \\ V_2 \end{bmatrix} = [b]$$