EE 40: Introduction to Microelectronic Circuits
Spring 2008: HW 9
(due 4/28, 5 pm)

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Referenced problems from Hambley, 4th edition.

1. P10.83

2. Design a clipper circuit for a negative limit of $-2.1V$ and a positive limit of $2.2V$. The input voltage is peak limited to $\pm 5V$.
   You are allowed to use two diodes, two d.c. voltage sources and a resistor.
   The maximum allowable current through each diode is $2.5mA$ and the threshold voltage of each diode is $0.7V$. Use an ideal voltage with threshold, ignoring breakdown.
   Hint: See Figure 10.32 in textbook.

3. A voltage source produces a periodic voltage $v_{in}(t)$ with period $T = 2s$ with waveform as in Figure 1. The positive peaks are of $6V$ and the negative peaks are at $-2V$. Note that

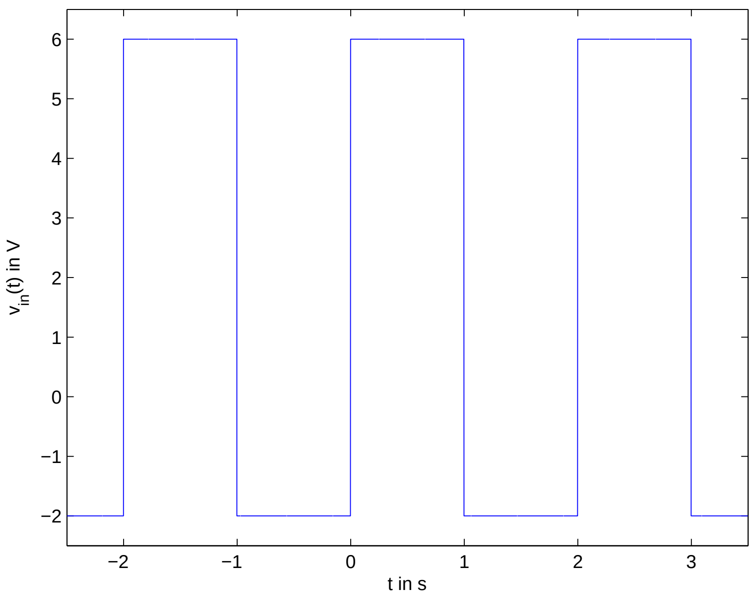

Figure 1: Waveform Input Voltage

$$v_{in}(t) = v_d + v_a(t)$$

where $v_d = 2V$ and $v_a(t)$ is a periodic signal with zero dc component.
It is desired to clamp $v_{in}(t)$ to a positive peak of $10V$. You are allowed to use at most one of each of the following:

(a) an ideal diode.

(b) an ideal Zener diode of arbitrary breakdown voltage.

(c) a resistor of size $1k\Omega$.

(d) a dc voltage source of arbitrary value.

(e) a capacitor of arbitrary value.

You may assume implicitly that there is a small resistance in series with the voltage source v_{in} which is so small compared to $1k\Omega$ that it can be neglected.
Design a clamp circuit to perform the desired task, giving some guidelines for the choice of values for the elements (b), (d), and (e).

4. In the circuit in Figure 2, the op-amp is assumed to be ideal. The circuit is called a *precision rectifier*.
Here $\pm V$ denotes the supply voltages. Take $V = 12V$. Note that $v_{out(t)}$ is defined at the $-$ input of

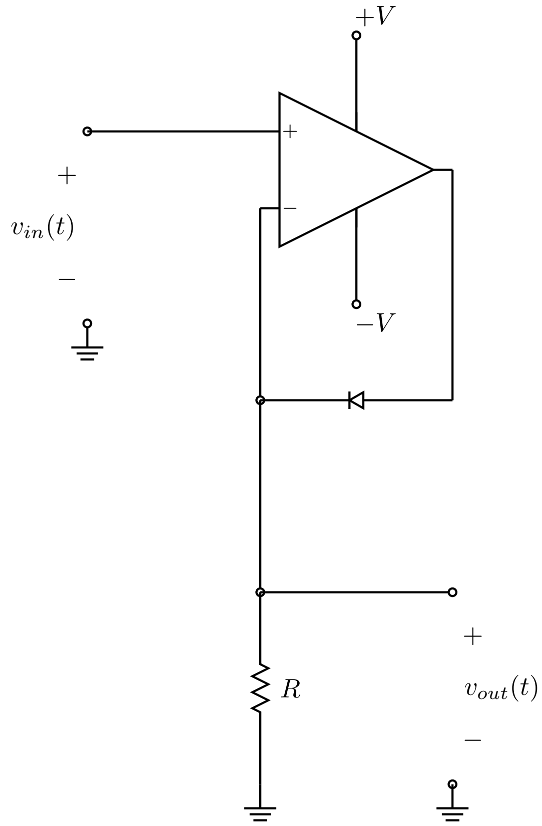

Figure 2: Precision Rectifier

the op-amp.

(a) Let $v_{in}(t) = V_m \sin(\omega t)$. Let V_m be significantly smaller than V, e.g. $V_m = 6V$. Determine $v_{out}(t)$ under the assumption that the diode is ideal.

(b) Now, suppose that the diode is modelled as having a threshold voltage $v_{th} = 0.7V$, being an ideal short circuit at threshold voltage and an ideal open circuit below the threshold voltage. Again, dtermine $v_{out}(t)$.

(c) Why is the circuit called a precision rectifier?

5. Consider the circuit in Figure 3. This circuit is known as an *inverting precision rectifier*.
Assume that the op-amp has supply voltages at $\pm 12V$ and that $v_{in}(t) = 6V \sin(\omega t)$. Further assume that the diode has a threshold voltage of $0.7V$ but is otherwise ideal.
Determine the voltage $v_{out}(t)$.

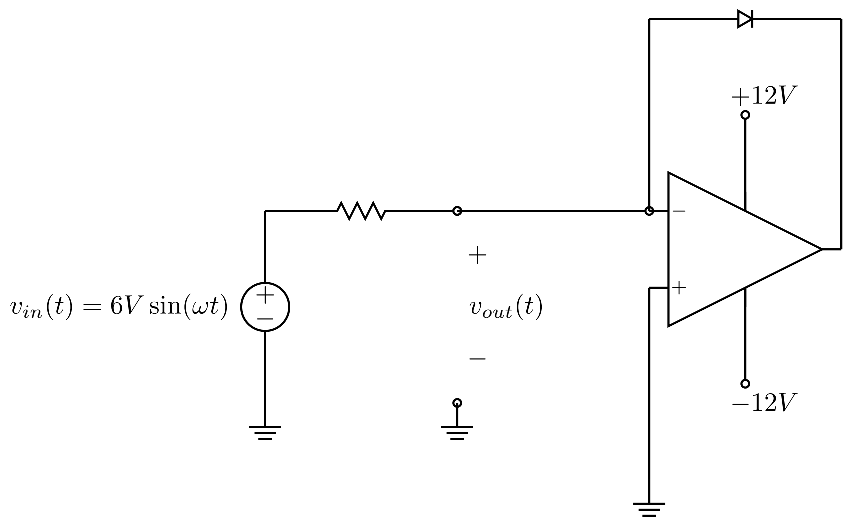

Figure 3: Inverting Precision Rectifier

6. For this problem, note that the intrinsic carrier concentration of both electrons and holes in pure Si at room temperature ($\approx 300K$) can be taken to be $10^{10}cm^{-3}$, while that in pure Ge can be taken to be $2 * 10^{13}cm^{-3}$.
   Identify the majority carrier and find the electron and hole concentrations at room temperature in the following semiconductors.
   (a) Silicon doped with phosphorus at a doping concentration of $10^{16}cm^{-3}$.
   (b) Silicon simultaneously doped with arsenic at a concentration of $5 * 10^{17}cm^{-3}$ and with boron at a concentration of $5.1 * 10^{17}cm^{-3}$.
   (c) Germanium doped with boron at a concentration of $2 * 10^{15}cm^{-3}$.

Consider a slat of silicon as shown in Figure 4. We focus on the x direction and assume that there is no

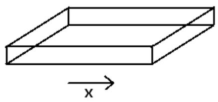

Figure 4: A slat of Silicon

variation in planes transverse to the x-direction.
Recall that Gauss's law tells us that if there is a charge density profile $\rho(x)$ in the slat (measured in $\frac{C}{cm^3}$) then the associate electric field E measured in $\frac{V}{cm}$ and with reference as pointing in the x direction is given by

$$\frac{dE}{dx}(x) = \frac{\rho(x)}{\epsilon}$$

Here, ϵ is the permittivity of the material (here, the material is silicon, for which you can take $\epsilon = 11.7\epsilon_0$, where ϵ_0, the permittivity of vacuum, is $8.85 * 10^{-14}\frac{F}{cm}$).
Further, the associated electrostatic potential $\Phi(x)$, measure in V, satisfies

$$E(x) = -\frac{d\Phi}{dx}(x)$$

which, together with Gauss's law, gives Poisson's equation

$$\frac{d^2\Phi}{dx^2}(x) = -\frac{\rho(x)}{\epsilon}$$

This determines potential differences: the actual value of the potential depends on a choice of reference. This discussion is relevant to the following three problems.

7. Suppose the charge density in a slat of silicon (variations only in the x direction) is given by the graph in Figure 5.

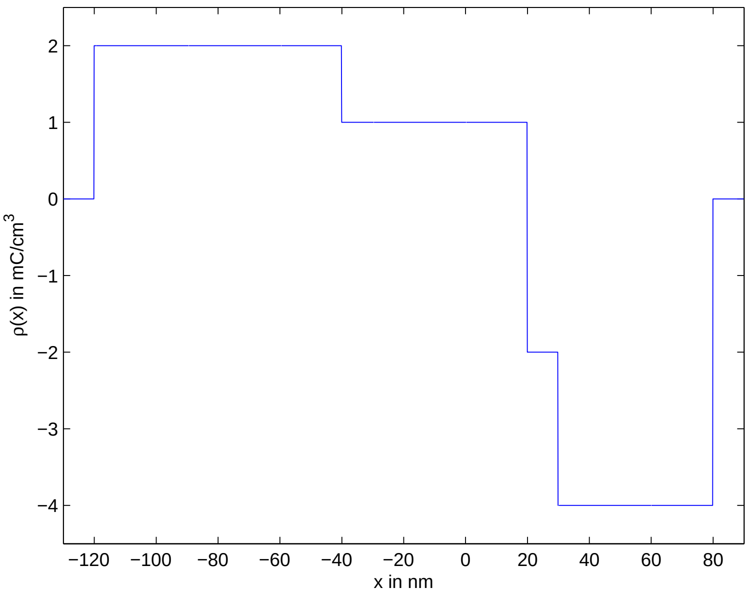

Figure 5: Charge Density Profile

   (a) Verify that the sample as a whole is electrically neutral.
   (b) Use Gauss's law to determine the electric field as a function of x.
   (c) Explain why the direction of the electric field (which is determined by its sign) does not change throughout the range $-120nm < x < 80nm$.
   (d) Determine the potential $\rho(x)$ as a function of x, assuming as a reference that $\rho 0 = 0$, thus solving Poisson's equation.

8. The electric field in a slat of silicon (variations only in the x direction) is given by the graph in Figure 6.

   (a) Determine the associated charge density $\rho(x)$.
   (b) Assuming as a reference that $\Phi(0) = 0$, solve for the corresponding potential $\Phi(x)$.
   (c) Verify that the sample as a whole is electrically neutral.

In addition to the discussion of Gauss's law and Poisson's equation, the following two problems refer to the depletion approximation for pn diodes.
In addition to the supplementary reader, you should also recall, as discussed in class, that, in the absence of an eventually applied bias, the potential in the bulk of the n-type material (away from the depletion region) can be taken to be $V_T \ln\left(\frac{N_d}{n_i}\right)$ and that in the bulk of the p-type material (away from the depletion region) can be taken to be $V_T \ln\left(\frac{n_i}{N_a}\right)$. Here $V_T = \frac{kT}{q}$ denotes the thermal voltage, n_i the intrinsic carrier concentration of holes and of electrons in pure silicon, and N_a and N_d respectively denote the doping densities of acceptors and donors (in the p-type and n-type materials, respectively).
The potentials are thought of as referenced to an "intrinsic" situation - if one solves Poisson's equation exactly with these boundary conditions, the potential will be zero precisely when the electron density and the hole density are equal (each equal to the intrinsic carrier concentration).

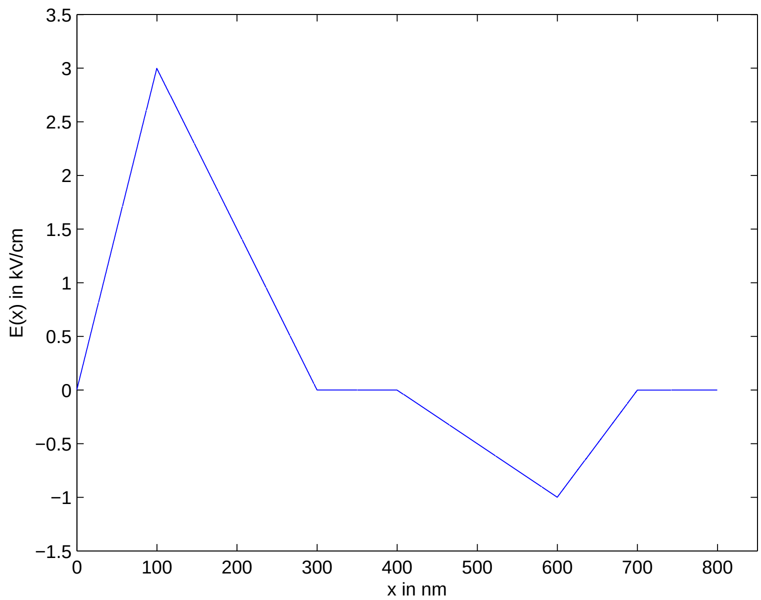

Figure 6: Profile of Electric Field

9. Consider a Silicon p-n junction in thermal equilibrium at room temperature with no externally applied bias. Assume that $N_a = 10^{19} cm^{-3}$ and $N_d = 10^{17} cm^{-3}$.
   Using the depletion approximation, determine the width of the depletion region in the n-type material, x_{n_0}, the width of the depletion region in the p-type material, x_{p_0}, the electric field $E(x)$ (as a function of the distance x from the junction, assuming the n-type region corresponds to positive x) and the potential $\Phi(x)$ as a function of x.
   Also determine the maximum magnitude of the electric field.

10. Repeat the preceeding problem for a Ge p-n junction in thermal equilibrium at room temperature with no externally applied bias, assuming that $N_a = 10^{17} cm^{-3}$ and $N_d = 10^{16} cm^{-3}$ using the depletion approximation.