Homework 2 EE 105 Solutions

Problem 1: Explain the key differences between conductors, semiconductors, and insulators in terms of their electrical conductivity and band structure. (5pts)

Conductor's electrical conductivity is very high. In terms of band structure, the conduction band is partially filled.

Semiconductor's electrical conductivity is moderate and can be controlled in some cases. In terms of band structure, there is a small energy gap between the valence band and the conduction band.

Insulator's electrical conductivity is very low. In terms of band structure, there is a large energy gap between the valence band and the conduction band.

Problem 2: An n-type semiconductor sample has a resistivity of 0.5 Ω·cm. If the sample is 2 cm long with a cross-sectional area of 0.1 cm², calculate its resistance. Now, imagine that I modify the semiconductor so that it is doped with 10 times *fewer* donors. What would the new resistance be, assuming the same geometry and carrier response to electric field (called mobility). (5pts)

$$R = \frac{\rho L}{A} = 10\Omega$$

For the n-type semiconductor, 10 times fewer donors means 10 times higher resistivity,

$$R^* = \frac{10\rho L}{A} = 100\Omega$$

Problem 3: Describe the crystal structure of silicon and explain how it contributes to its semiconductor properties. Describe why silicon and other materials, such as InP, InAs, GaAs, etc are semiconductors. (5pts)

Silicon (Si) crystallizes in a diamond cubic structure, and Each silicon atom forms four covalent bonds with its neighboring silicon atoms, and the strong covalent bonding ensures a well-defined energy band structure, with a band gap of 1.12 eV at room temperature, making Silicon a semiconductor**.**

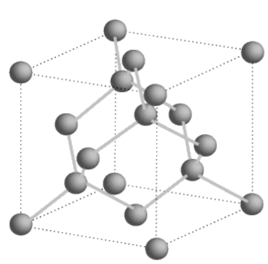


Figure 1.Silicon diamond cubic crystal structure

On the other hand, materials like InP, InAs, GaAs, etc. are semiconductors because they are in zinc blende structure and zinc blende structure is essentially the same with diamond cubic structure other than it's made of 2 types of atoms instead of 1 type. Each atom forms four covalent bonds with its neighboring atoms, and the strong covalent bonding ensures a well-defined energy band structure. For further reading, one might find this interesting.

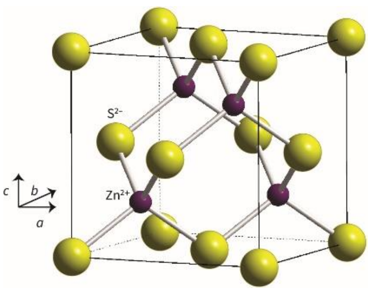


Figure 2. Zinc blende, or ZnS, is also a semiconductor

Problem 5: A silicon diode is forward-biased with a voltage of 0.7 V at room temperature (300 K). Calculate the diode current if the reverse saturation current I_0 = 1 nA. (5pts)

$$I = I_0(e^{\frac{V_d}{nV_T}} - 1)$$

At $V_d = 0.7V$

$$I = I_0\left(e^{\frac{V_d}{nV_T}} - 1\right) \approx 574.75A$$

It's too high to be reasonable. However, it does show that the diode starts to conduct and current flows at $V_d = 0.7V$.

Alternatively, you can talk about whether it's possible to maintain the V_d at 0.7V or higher at this setting.

Problem 6: Explain the significance of the invention of the transistor in the development of modern electronics. (10pts)

Compared to vacuum tubes, transistors are small, lightweight, and highly efficient, leading to miniaturization of electronic devices.

Problem 7: A MOSFET has a threshold voltage VT = 1 V. If the gate voltage VG = 3 V and the drain-source voltage VDS = 2 V, determine the operating region of the MOSFET. (10pts)

Since $V_{DS} = V_{GS} - V_T$, the MOSFET is at the boundary between the triode and saturation regions.

Problem 8: Describe how a CMOS inverter works and explain its advantages in digital circuits. (10pts)

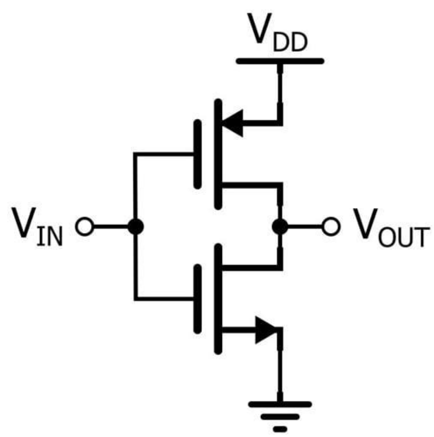


Figure 3. A CMOS inverter

The PMOS transistor is connected between the positive supply voltage (VDD) and the output node. The NMOS transistor is connected between the output node and ground (GND). Both transistors have their gates tied together and connected to the input signal. When the input is low (0), the output is high (1). When the input is high (1), the output is low (0).

Problem 9: Design two different CMOS logic gates to implement the following two truth tables. (10pts)

The left truth table is describing a NAND (not + and) gate, while the right one is describing a NOR (not + or) gate.

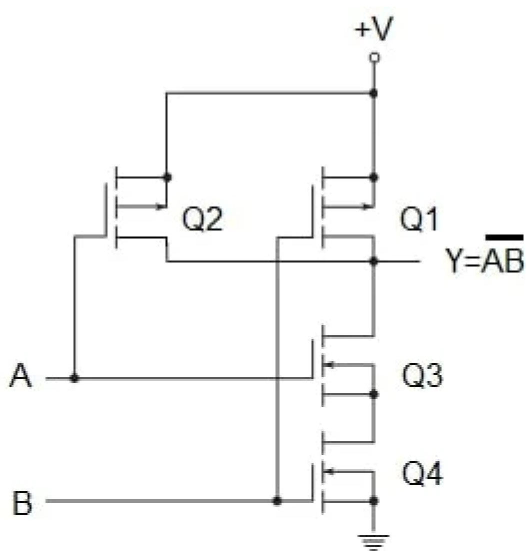


Figure 4. A CMOS NAND gate

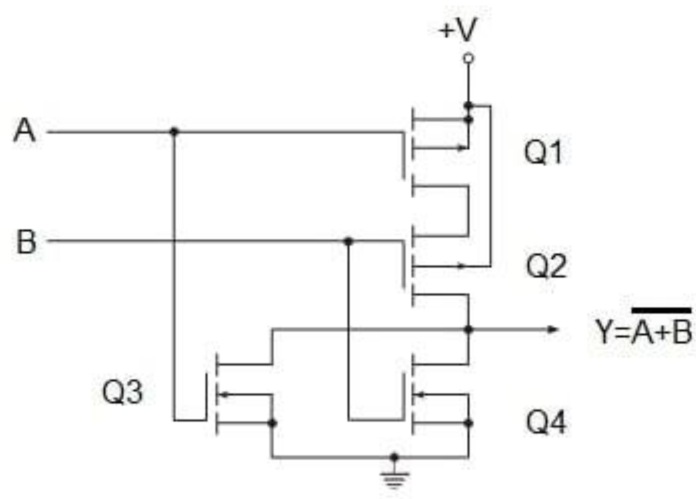


Figure 5. A CMOS NOR gate

Problem 10: Explain the ideal characteristics of an operational amplifier and discuss how real op amps deviate from these ideal properties. Include in your explanation the concepts of open-loop gain, input impedance, and output impedance. (10pts)

An ideal operational amplifier (op-amp) has infinite open-loopg, infinite input impedance and zero output impedance. In real op-amps, the open-loop gain is finite and can vary between 10,000 and 1,000,000, depending on the op-amp type. Typically, the gain is high but not infinite, and it decreases with frequency. This means that the op-amp may not be able to fully amplify small differences between inputs at higher frequencies. Real op-amps have high but finite input impedance. Typically, op-amps have input impedances in the range of 10^5 to 10^{12} ohms, depending on the design. However, they do draw a small current at the input terminals, which may affect the circuit, especially in high-impedance sources. Real op-amps have non-zero output impedance, usually in the range of 10 to 100 ohms. While this is small compared to the load impedance, it can cause voltage drops when driving low-impedance loads.

Problem 11: An inverting amplifier circuit uses an op amp with a 10 kΩ feedback resistor (Rf) and a 2 kΩ input resistor (Rin). If the input voltage is +0.5 V: (10pts)

a) Calculate the output voltage

b) What happens to the output voltage if the input voltage polarity is reversed?

c) Explain why this configuration is called an "inverting" amplifier.

$$V_{out} = -\frac{R_f}{R_{in}} V_{in} = -5 * 0.5V = -2.5V$$

if the input voltage polarity is reversed, the output voltage will be positive and equal to +2.5V. This configuration is called an "inverting amplifier" because the output voltage is inverted in polarity relative to the input voltage.

Problem 12: Design a non-inverting amplifier circuit that produces a gain of exactly 4.75. Specify the resistor values you would use if you have standard resistors available in the E24 series. Calculate the expected output voltage if an input of 1.2 V is applied to your circuit. (10pts)

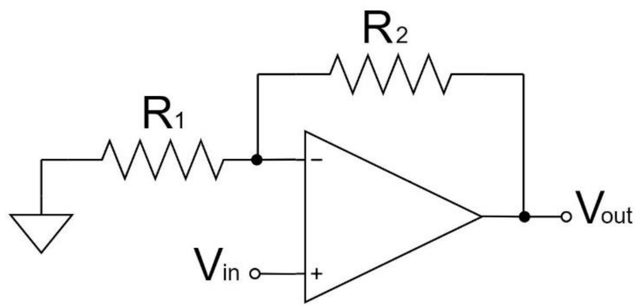
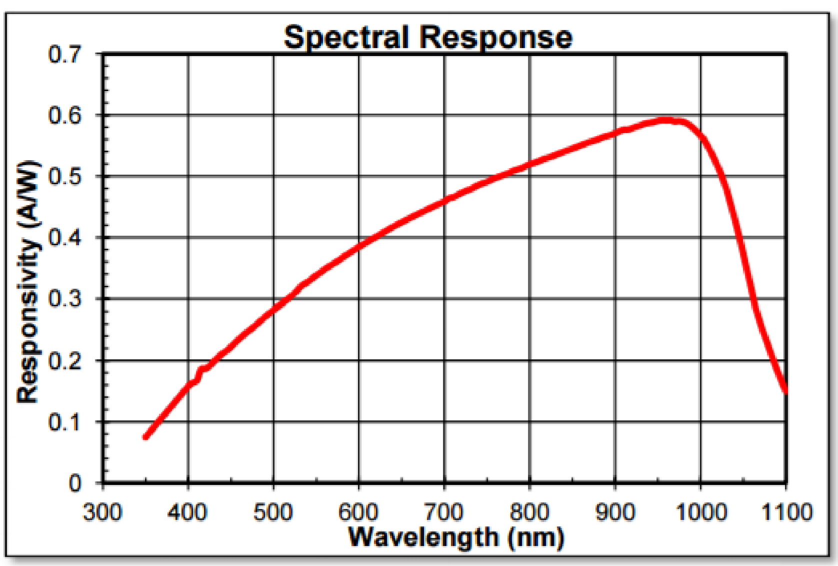


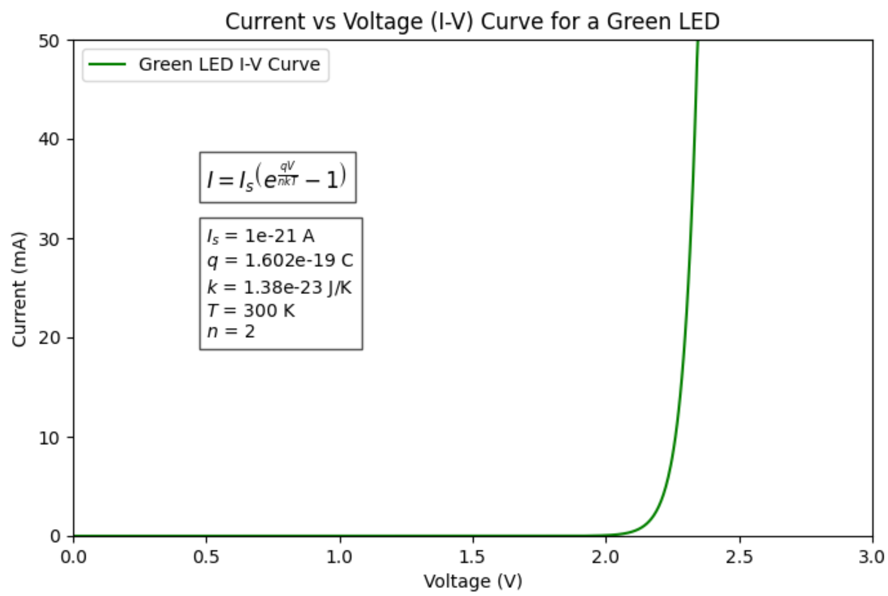
Figure 6. Non-inverting Op-Amp circuit

For non-inverting amplifiers, $A = 1 + \frac{R_f}{R_{in}}$. If A=4.75, $\frac{R_f}{R_{in}} = 3.75$. We can begin by using a $R_{in} = 1000\Omega$. This means we need to use we find a $R_{in} = 3.75k\Omega$, which can be constructed by connecting a $3k\Omega$ and a 750Ω resistor in series. The expected output voltage if an input of 1.2 V is applied to your circuit is 5.7V.

Problem 13: Imagine you have a green LED (emission wavelength = 532 nm), and a silicon photoetector with a responsivity as shown below. (10pts)



Your LED has a diode I-V curve as shown below. Assume a quantum efficiency of current to photon generation of 30%.



Now, calculate what the current in the photodiode will be as a function of the current in the LED, assuming that 10% of the light emitted by the LED falls on the photodiode.

If the dark current in the LED is 10^{-10} A, what is the minimum amount of voltage you will need to apply to the LED in order to be able to measure anything on the photodetector?

Electrons per second $I_{led} = n_e e$, where $e = 1.6 \times 10^{-19}\ C$ is the charge of a single electron, so $n_e = \frac{I_{led}}{e}$.

Photons per second landed on PD, $n_p = 30\% * 10\% * n_e = 0.03 * \frac{I_{led}}{e}$

Energy of a single photon $E_p = \frac{hc}{\lambda} = 3.73 * 10^{-19} J$

Optical power, $P_p = E_p * n_p = 1.119 * 10^{-20} * \frac{I_{led}}{e}$

According to the first figure, $I_{pd} = 0.3 * P_p = 0.3 * 1.119 * 10^{-20} * \frac{1}{1.6\times10^{-19}} * I_{led} \approx 0.02 I_{led}$

Let's say we got some really advanced equipment that we can detect a I_{pd} as low as 1nA. In this case, $I_{led} = 50nA$. Solve the equation ,

$$I = I_0(e^{\frac{V_d}{nV_T}} - 1)$$

we got $V_d = 0.32V$