

ELE 208 Spring 2014  
Princeton University  
**Problem Set Question Bank**

Hey Folks,

**Welcome to ELE 208!**

**This is an experiment.** Instead of keeping you in the dark, we are giving YOU, at the start of the semester, all the questions that you will solve as a part of your weekly problem set throughout this semester. This gives YOU a lot of flexibility in terms of when you want to solve these problems. You could do it as and when the material is taught in class. Or you could choose to do it the night before the due date. Your call. However, I will tell you that a lot of the questions are set up such that you would need to think hard before answering them. At the same time, I also promise that none of these questions would be just mind-numbing arithmetic or number crunching. ALL of the problems below will be interesting, engaging and hopefully, a great learning experience.

As part of your evaluation, you will be asked to solve certain questions from here for each week and a due date would be set depending upon the number of questions to be solved and their difficulty.

Each question starts with few phrases in bold that is the central theme for that question. Each of them will have many sub-parts that often builds upon one another. It would be to your advantage to read through them carefully and answer them in sequence.

A lot of the questions you will encounter can be difficult and open-ended, but never impossible. I have often found that discussion definitely helps with understanding the material and being able to solve the problems. However, I do ask each of you to write up your own solutions, independently of others. In the spirit of communal learning, I also ask you to not work out complete solutions as a group and merely reproduce the same answer on multiple copies. I hope you will adhere to this honor code. Good luck with your assignments.

A lot of the questions will ask you to discuss a particular result or justify your answer. In this context, please remember that brevity is not just the soul of wit, it's a harbinger of higher grades!

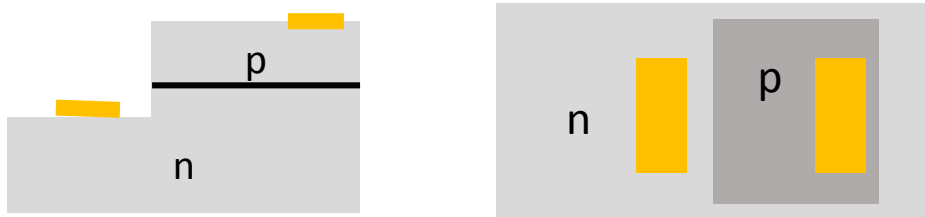
**(\*)Star marked questions:** These questions are on the analytic side and would be more difficult than the rest (specially made for our beloved students). I do not expect you to give complete solutions. Answer these questions as best as you can. Discussing these would result in a much better understanding of the material.

Good luck throughout the semester!

ELE 208 Team!

**1. Simple device processing:** Light emitting diodes (LEDs) emit light when current is injected through the structure. Most simple LEDs consist of a p-n junction, each with its own metal contacts. (Do not worry about the technical terms, you only have to focus on processing issues). Light is often collected from the top of the device and therefore the top metal contact needs to have a ‘window’ as shown in the figure, which gives the top and side view of the device you will fabricate. You are given a square 1 cm x 1 cm wafer of the LED,

- Using fairly neat sketches (Straight lines should look straight, although I don’t expect a scale drawing), give a detailed description of the processing steps from the wafer to the device. Be aware of undercut in your drawings. (You do not need to give the exposure times / etching solutions / etc., just the process sequence would suffice).
- Make drawings of the optical mask set required for fabricating the above structure.



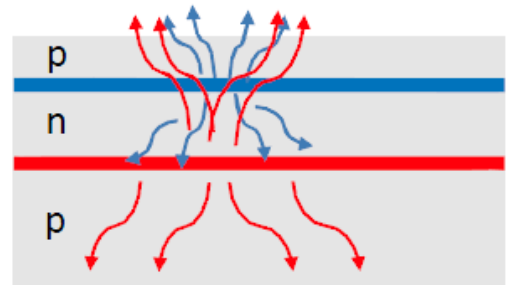
**2. Optical Lithography:** Photoresists are comprised of 3 components – the photoactive polymer (that reacts to UV light), a resin to keep the polymer stable and a solvent to dissolve everything in. After spinning the photoresist, you bake the sample to evaporate the solvent. UV light reacts with the photoactive polymer thereby converting it to an organic acid. Now, the developer solution you use is a base. What happens when you ‘develop’ photoresist is that the acid that is formed by the reaction with UV reacts with the base from the developer and gets converted to a soluble salt and water, and voila! you have your pattern. Some of you might have made mistakes when you were doing it for the first time and would have been told as to what went wrong by the TAs. Now, for the purposes of this problem, it’s your job to be an AWESOME TA for 3 students who are doing their first lithography.

Alice, Bob and John are being introduced to the concept of optical lithography for the first time. They are each given a piece of Silicon wafer and identical set of masks consisting of straight lines 5  $\mu\text{m}$  wide, separated by 10  $\mu\text{m}$  from each other. To make fair comparisons, all 3 students are asked to use the same photoresist (AZ 1518) and developing solution (AZ300 MIF). They were all told to spin the photoresist at 4000 rpm for 40 seconds. After about 30 minutes, all 3 students come to you to show their finished product post lithography. Not surprisingly, each of them had made a mistake in their process and therefore their intended pattern did not turn out well. Following are the notes in their lab notebooks, upon observations of the sample as seen under an optical microscope. Your job is to identify what mistake each of the student committed (It IS possible that one student did multiple mistakes) and identify a solution to rectify the mistake. (Multiple correct solutions are possible, write

down as many as you can think of. DO NOT write everything that you know about lithography for each of them.)

- a. Alice: "Pattern looks completely washed out, no clear lines observed and very watery film on the surface of the sample."
- b. Bob: "Pattern correctly formed – however, thickness of the lines were 5.5  $\mu\text{m}$ , and they were separated by approximately 10  $\mu\text{m}$ . Also, photoresist was not completely gone from areas where they shouldn't have been present."
  - i. Do you think the student should have developed longer?
  - ii. What if the student did develop long enough, and still the observations did not change?
- c. John: "Pattern correctly formed. The lines were now only 2.5  $\mu\text{m}$  wide, and they were separated by  $\sim 10 \mu\text{m}$ ."

3. **2-color patterned LEDs:** Figure 2 shows the cross section of a 2-color LED wafer – the longer wavelength red can pass through the shorter wavelength blue and therefore, both colors can be observed from the top. Each of the LEDs in the stack can be operated independently or together, depending upon the type of etching and electrical contact you make. Your task here is going to be able to design a 2-color LED that displays two initials of your name on top of each other as shown in this figure. For the purposes of this assignment, make detailed sketches of the optical mask set needed for fabrication of this LED. (Do not worry about processing steps, or the look of the finished device). (NOTE: Even though theoretically possible, do not pick the same letters as your initials. That is not being smart and will not fetch full credit).



4. **Optics of Lithography:** What we have left out in our discussion of lithography is the physics of UV light and its interaction with the mask and the sample. What determines, to a large extent, the reproduction of the mask pattern on to your sample is the feature dimension on the mask and the separation between the mask and your sample. Consider, for now, a situation where you are trying to reproduce a pattern that consists of straight lines that are  $x \mu\text{m}$  wide and separated by  $y \mu\text{m}$  each (much as in Problem 2, but  $x$  and  $y$  will vary throughout this problem).

For the first scenario, assume that the separation between your mask and the sample is zero (ideal case, your sample is in contact with the mask). Also, assume that ideal conditions are followed and that there are no issues with the fabrication itself. The wavelength of UV light used in lithography is fairly broadband, but can be assumed to be around 300 nm. In each of the following cases, discuss whether the pattern will completely develop with the correct dimensions giving a 1 or 2 sentence reasoning for your answer. If you were to look at the sample after developing under an optical microscope, what would you see?

- $x = 500 \text{ nm}$ ,  $y = 500 \text{ nm}$ . Think about what will happen to patterns when their dimensions approach the wavelength of the UV light.  
*Hint:* What happens when light encounters small gratings similar in size to its wavelength?
- $x = 10 \text{ }\mu\text{m}$ ,  $y = 10 \text{ }\mu\text{m}$ .
- (\*)  $x = 5 \text{ }\mu\text{m}$ ,  $y = 500 \text{ nm}$ . This is an interesting case. What do you think will happen?

(\*) For the second scenario, assume  $x = 10 \text{ }\mu\text{m}$  and  $y = 10 \text{ }\mu\text{m}$ . However, in this situation, there arises a gap between the sample and the mask. For each of the given situations, explain how the pattern would look after developing. Qualitative answers and reasoning are sufficient. (Eg., the developed pattern would be smaller or larger than  $10 \text{ }\mu\text{m}$ , etc.)

- Gap between sample and mask =  $0 \text{ }\mu\text{m}$ .
- Gap between sample and mask =  $1 \text{ }\mu\text{m}$ .
- Gap between sample and mask =  $100 \text{ }\mu\text{m}$ .

**5. Foundations of Quantum Mechanics:** In this problem, we'll compare quantum mechanics (QM) and classical mechanics (CM).

- Consider a classical billiard ball on a pool table moving with a constant velocity,  $v$ . Write down an expression for the total energy,  $E$ , of the ball. Assume that the height of the table is  $h$ .
- Re-write the above expression in terms of the momentum,  $p$ , of the ball. ( $p = m \cdot v$ )
- Let's 'quantize' the above equation. The total energy,  $E$ , is still the same. The classical potential energy you wrote above is just the potential,  $V$ , in QM. The kinetic energy is a little more complicated. Assume for now that momentum in QM is written as  $p = i\hbar \frac{d}{dx}$  where  $i$  is the imaginary number ( $\sqrt{-1}$ ),  $\hbar$  is the reduced Planck's constant ( $h/2\pi$ ) and  $\frac{d}{dx}$  is the first derivative with respect to space. Using this information, rewrite the equation in (b).

*Hint:*  $\left(\frac{d}{dx}\right)^2 = \frac{d^2}{dx^2}$

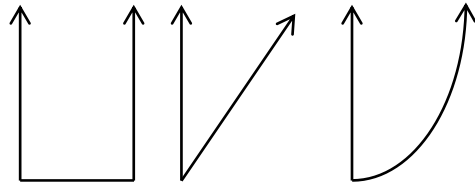
- What you just did above is the signature of quantum mechanics. You took a classical quantity,  $p$ , and converted it into an operator  $i\hbar \frac{d}{dx}$ . In QM, we deal with operators. These now act upon what you call a wave function,  $\psi$  – a purely quantum mechanical construct, to give measurable quantities. Operate the above equation you wrote in (c) on a wavefunction  $\Psi$ , and rearrange to get Schrodinger's Equation. Write it down.
- What does (c) and (d) tell you about the nature of quantum mechanics?
- Now, consider the billiard ball and an electron. Let's put the ball in a 'potential' well that's  $10 \text{ m}$  deep. Let's put the electron in a finite potential well,  $V$ . For now, let us also assume that the ball has a wavefunction  $\psi_b$  and the electron's wavefunction is  $\psi_e$ .
  - What is the 'potential' in each of the two systems?
  - Write down the boundary conditions for the two wavefunctions,  $\psi_b$  and  $\psi_e$ .
  - What distinctive difference do you see in the above boundary conditions that expresses the quantum nature of the electron?
  - Do you think the energy of the billiard ball is also discrete and quantized? Justify.

- v. What is the probability of finding each of the two 'objects' outside its respective potential wells?

**6. Infinite Potential Wells:** In this problem, you will explore infinite wells and understand how its properties vary with different parameters. Let us recall that the Energy of the  $n^{\text{th}}$  level is:  $E_n = \frac{n^2\pi^2\hbar^2}{2mL^2}$  where  $n$  is Energy level quantum number,  $\hbar$  is the reduced Planck's constant ( $\hbar/2\pi$ ),  $m$  is electron mass and  $L$  is the length of the quantum well.

Now, consider that you have two infinite potential wells of length  $L_1$  and  $L_2$  where  $L_2$  is twice that of  $L_1$ , and that they are very far away from each other so that there is no interaction.

- Draw the first few energy levels and wave functions in the two wells. Levels in the two wells should be relatively consistent.
- Now, consider that the wells are  $10*L_1$  apart. Would the energy levels and wavefunctions change in either of the wells? Would you have electrons tunneling between the wells?
- Now, consider that the wells are  $2*L_1$  apart. How would your answer to (b) change? Draw the energy levels and wavefunctions in both the wells for this case.
- (\*) Now, you will differentiate the energy levels and wavefunctions in three different infinite potentials – a square well, triangular well, and a quadratic well as shown in the figure below. Note that the potential goes to infinity in all three case, but the rate at which they go is different. Draw the energy levels and wavefunctions in the three potentials side-by-side with the correct relative positions of the energy levels. Justify your answer.



- (\*) All along, we have studied time independent Schrodinger equation and quantum mechanics. Let's see what happens when we bring time into the picture. For this part, assume that we have only one infinite potential well with length  $L$ . You already know the energy levels and wavefunctions of this system. At time  $t=0$ , the well suddenly expands to a new length  $L'=2L$ .
  - How will the energy levels and wave functions look immediately after  $t=0$ ?
  - How will the energy levels and wave functions look a long time after the sudden change?

*Hint: Remember that wavefunctions and its derivatives are continuous. Sudden changes in potential will also suddenly change the boundary conditions. However, the wavefunctions represent real systems (in this case, the square of the wavefunction represents the probability density of the electron) and therefore cannot change suddenly.*

**7. Finite potential wells and boundary conditions:** Consider a finite well of potential  $V$  and width  $L$  centered about the origin.

- Easy one:* Draw the relative energy levels and wavefunctions for this potential well.
- Another easy one:* Write down the Schrodinger equation in the different regions of the quantum well, and the associated boundary conditions.
- The actual solutions to the Schrodinger Equation that you wrote in (b) in the different regions are given below, along with constants  $A$  through  $F$  that needs to be computed.  $\alpha$  and  $\beta$  are the electron wave vectors in the different regions and can be treated as constants (you do not have

to worry about this for the purposes of this problem). As you can already see from the equations below, the wavefunction is sinusoidal inside the well and exponential outside it.

$$\Psi = \begin{cases} Ae^{\alpha x} + Be^{-\alpha x} & x < -L/2 \\ C \sin(\beta x) + D \cos(\beta x) & -L/2 < x < L/2 \\ Ee^{\alpha x} + Fe^{-\alpha x} & x > L/2 \end{cases}$$

Using the boundary conditions that you wrote down in (b) for the different regions, evaluate or eliminate as many constants (A through F) as possible in the above wavefunctions. This is going to be a bit of algebra, so writing down the different terms neatly would greatly help with the math. Can you eliminate all the constants with the given boundary conditions? *Hint:* First eliminate constants using boundary conditions at  $x = \pm \infty$ .

- d. If you had done the previous part correctly, you would be left with only one constant. Without any math, can you think of a way how this constant can be calculated? Do not google the answer.
- e. **(\*) Tunneling:** The probability of finding the electron outside the well is finite. This is what we mean when we say that an electron can tunnel out of a potential well. Answer the following questions qualitatively with justification. You do not need to do any more algebra. While answering the following questions, remember that the probability of finding an electron goes as the square of the wavefunction.
  - i. Let  $L=10$  nm. Assume that there are 2 similar wells each of width 10 nm. Will electrons tunnel between the wells when they are 1000 nm apart in space?
  - ii. What if the two wells are only 15 nm apart? How can you calculate the probability of tunneling (Just give an idea of how it can be computed)?
  - iii. Based on your answers to the above question, how will a plot of tunneling probability as a function of separation distance between the wells look? Sketch a curve which you think is the answer and justify it. What do you think is the most likely form of this curve – will it be linear, or quadratic, or exponential? Why?

**8. Crystal structures:** The face-centered cubic (FCC) is usually the go-to crystalline structure for most (at least the useful ones) important semiconductors like Silicon and GaAs.

- a. Draw the side and top view of the FCC lattice.
- b. Draw the side and top view of a fictitious crystal that has an FCC lattice and two different atoms (A and B) in the basis.
- c. Now, do as instructed in (b) for an alloy  $A_xC_{1-x}B$ .
- d. Draw the side and top view of an amorphous semiconductor crystal.

**9. Basics of bandstructures:** By now, you must have seen quite a number of band structures of semiconductors. You should also know that y-axis is the Energy and x-axis is the wave-vector or the momentum of the electron.

- a. In general, what is the relation between wavelength ( $\lambda$ ) and wave vector ( $k$ )?
- b. As you might know, electrons behave both as particle and waves, often termed as the wave-particle duality. This concept was brought forth in a brilliant yet simple equation by Louis de Broglie, which relates the wavelength ( $\lambda$ ) of a matter wave (wave-nature) to its momentum ( $p$ , particle nature). This relation is given by,  $\lambda = \frac{h}{p}$  where  $h$  is the Planck's constant. Using this and

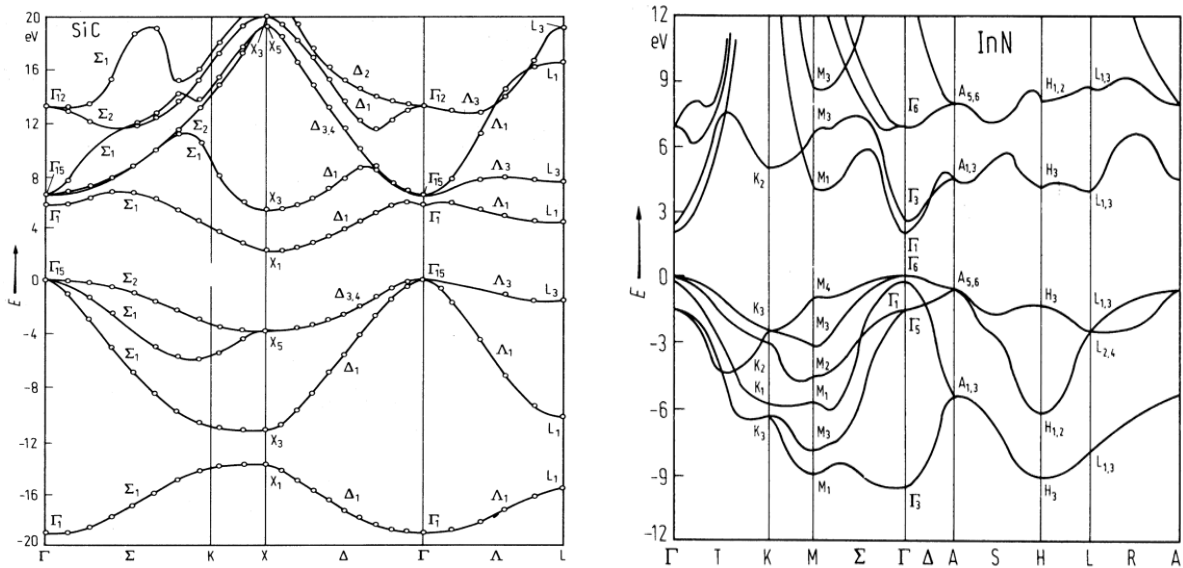
your answer to part (a), prove that the wavevector on the x-axis of a band diagram is indeed the momentum of electron differing by only a constant multiplier.

- c. Now you've figured out that the x-axis is indeed the momentum of an electron. We will now figure out why it has to be so, instead of say, position, with a simple calculation.

The Uncertainty Principle, invented by Werner Heisenberg, states that due to the quantum nature of matter, it is impossible to precisely measure both the position and momentum of a particle simultaneously. Formally put, this relation can be written as  $\Delta x \cdot \Delta p \geq \frac{h}{4\pi}$  where  $\Delta x$  is the uncertainty in position,  $\Delta p$  is the uncertainty in momentum and  $h$  again, is the Planck's constant.

- As you know, an electron's wavefunction inside a crystal is highly de-localized. This means that an electron's influence extends way beyond a single lattice period. Assume that the wavefunction (position, really) is localized over a distance of 100 nm – that's your uncertainty in position. Using the above relation, calculate the uncertainty in momentum,  $\Delta p$ .
- Now, calculate the average momentum of an electron in a crystal. Assume a typical velocity of  $10^7$  cm/s and an effective mass of 1.
- What is the percentage error in knowing the momentum of an electron in a crystal?
- What is the percentage error in knowing the position of an electron in the crystal? Assume that typical  $x$  values are about 1 nm.
- Now, explain based on your simple calculations, why x-axis is momentum and not position.

**10. Band Structures and Absorption:** Consider the band diagrams of 2 materials given below (a) Silicon Carbide (SiC – incidentally, one of the hardest known material to man) and (b) Indium Nitride (InN).



From your knowledge of band structures learnt in class and the previous problems, answer the following questions:

- For both the materials, identify whether it is a direct or an indirect band gap semiconductor and give the approximate value of the band gap.
- Mark the band edges for both the materials.
- Where would you most likely find free electrons and holes in each of these systems?

- d. Mark with arrows the regions where (i) absorption and (ii) emission will likely occur in these materials?
- e. Which of the materials will have a stronger emission? Why?
- f. (\*) Which of the materials will have a stronger absorption? Why? Think carefully before you jump to an answer.
- g. (\*) Absorption spectra refers to a plot of absorption intensity as a function of energy. Absorption depends on the number of initial and final states of the electron. For bulk semiconductors, these states (both in the valence and conduction band bands) go as the square root of Energy, i.e., the density of states is proportional to  $\sqrt{E}$ . With this information, plot a rough sketch of the absorption spectrum of the two materials, SiC and InN. Justify your solution by pointing out key similarities and differences between the two plots.
- h. (\*) **Defect Levels:** It often happens during semiconductor fabrication that defects get into the semiconductors. Let's start with Silicon, the most common and well-studied *indirect band-gap* semiconductor. Gold is a well-known deep level defect in silicon. Gold atoms replace silicon atoms in the crystal structure. While this does not alter the band structure much, what it does is *create a narrow empty level in the middle of the band gap*. Now electrons, instead of making a transition to the conduction band or the valence band, gets caught in these defect levels and changes various extrinsic properties of devices made with silicon. One prominent effect is that the threshold voltage of transistors change (you will study about this later in the course).
  - i. First, draw a schematic of the band structure of silicon, with and without the defect level. Denote the defect level by a straight line.
  - ii. Second, draw a rough sketch of the absorption spectrum of Silicon without any defects.
  - iii. Now, re-draw the absorption spectrum with Gold impurities in silicon. Note that there are only a finite number of empty states in the defect level.

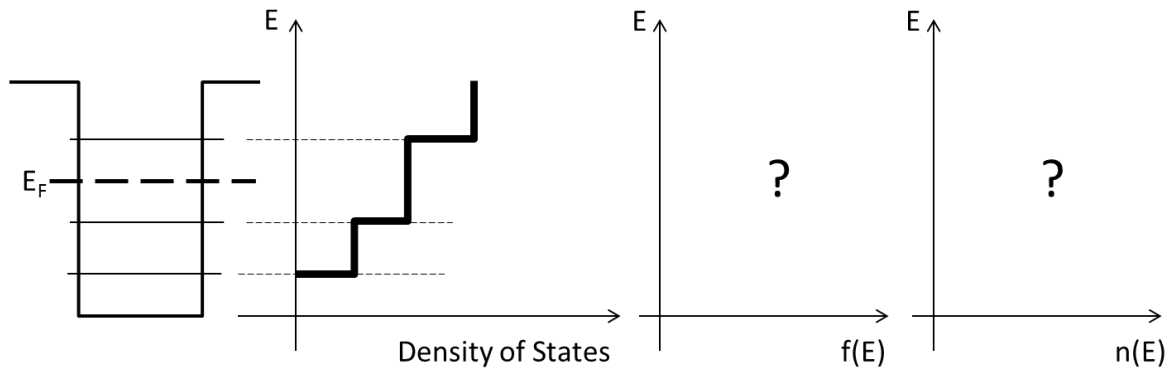
**11. Fermi level, Temperature and Doping:** Consider 2 direct band gap semiconductors, one with a band gap of 1 eV and the other with a band gap of 2 eV. These structures are not doped.

- a. Draw the Fermi level in both the materials.
- b. Assume that the Fermi level is in the middle of the band gap in both the materials. Draw the Fermi function at (i)  $T = 0$  K, and (ii)  $T = 300$  K.
- c. At a given temperature, say, 500 K, which material will have more electrons in the conduction band? Why?
- d. (\*) Now, calculate the ratio of electrons in the conduction band at 500 K in the two materials. Assume that the density of states is constant and the same for both the semiconductors. Also approximate the Fermi function by the Boltzmann distribution in the region of interest.
- e. (\*) Let's say I put an electron inside the conduction band of the semiconductor with a direct band gap of 1 eV. Given this scenario, what are possible actions available for this electron under the following conditions? Also, mention and justify which one of those is most likely?
  - i. When the temperature of the system is 0 K.
  - ii. When the temperature of the system is 300 K.

**12. Density of States:** You learnt in class that the number of electrons (holes) in the conduction band (valence band) not only depends on the Fermi function, it also depends on the density of states.



- Using the above statement, can you explain why there are no electrons in the band-gap of a semiconductor?
- Now, consider a finite quantum well with 3 energy levels and a Fermi level as shown, together with the density of states. Assume a temperature of 0 K, draw the Fermi function with the y-axis as Energy and x-axis as  $f(E)$  where  $f$  is the Fermi function.



- Using the given DoS and the  $f(E)$  you have drawn in (b), qualitatively draw the electron density (number of electrons) as a function of energy in the system.

### 13. Semiconductor dynamics:

- Make 3D surface plots of mobility vs temperature vs carrier concentration for the following. You may consult the 2D figures for mobility vs temperature and mobility vs impurity concentration in chapter 8 of the textbook.
  - Ge:As (n-type Ge)
  - GaAs (both n and p types)
- Calculate the room temperature resistivity for the following cases. Use Fig. 8.6 in your textbook.
  - p-type Ge with a doping concentration of  $10^{17} \text{ cm}^{-3}$ .
  - n-type Si with a doping concentration of  $2 \times 10^{17} \text{ cm}^{-3}$ .
  - p-type GaAs with a doping concentration of  $10^{16} \text{ cm}^{-3}$ .

### 14. Basic p-n junction: Consider a p-n homo-junction initially at zero bias.

- Draw the steady-state band diagram for this device.
- Aligned with the band diagram that you just sketched, draw the charge distribution, electric field and potential as a function of space. Give expression for maximum electric field, total charge enclosed, etc. on your plot using appropriate variables for depletion region width and doping.
- Now, consider that the p-side of this junction was not doped uniformly. Now, the p-side has step doping where the half close to the junction has 3 times higher doping than the half away from the junction. Draw the band-diagram of the junction in this scenario.
- (\*) Draw the forward bias band diagram for the situation in (c). Where will the applied voltage drop? Give careful consideration.

### 15. Theory of compensation: Consider a p-n junction with doping $N_A = 5 \times 10^{17} / \text{cm}^3$ and $N_D = 1 \times 10^{17} / \text{cm}^3$ .

- Using expressions from the text book, calculate the electric field and junction potential as a function of distance. Assume that the p and n-side are much longer than the diffusion length.

- b. Now, the p-side of the device is slowly injected with n type dopants according to the following equation:  $N_p(t) = N_D^\infty(1 - e^{-t})$  ( $t \geq 0$ ) where  $N_p(t)$  is the n-type dopant density on the p-side at time  $t$  and  $N_D^\infty = 1 \times 10^{18} / \text{cm}^3$  is the final n-type dopant concentration on the p-side. Plot the concentration of n-type dopants on the p-side as a function of time. What kind of a junction do you have now?
- c. What is the total number of dopant atoms on the p-side? How about the net charge carriers?
- d. For the case in (b), plot the charge density on the p-side as a function of time. Evaluate all 'important' points in your plot.

(\*) Conceptually answer the following questions.

- e. (\*) When will the depletion width be minimum? When will it be maximum?
- f. (\*) Plot the variation of  $|E_{\text{max}}|$  as a function of time. Does the position at which you have maximum field vary with time? Justify.
- g. (\*) Is there a time when  $E_{\text{max}}$  is zero? If yes, calculate it. If not, give reasons.
- h. (\*) Considering the entire structure as a whole, what is the built in potential at  $t = 0$  and  $t = \infty$  (use expressions from your text)? Plot how this built-in potential changes as a function of time.
- i. (\*) Considering the entire structure, how will the size of the depletion region vary with time? Answer with a qualitative sketch.
- j. (\*) Will you expect to see a change in the mobility of the carriers that is different from the bulk electron/hole mobilities? Why or Why not?
- k. Will you expect to see a change in the conductivity of the carriers that is different from the bulk electron/hole conductivities? Why or Why not?

**16. P-I-N junctions:** Consider a p-n homojunction (say, Si) that is used as a solar cell. In a solar cell, the electron-hole pairs generated by sunlight is swept away to the contacts via the built-in field in the p-n junction. It has been found that having an intrinsic (un-doped) region between the p and the n side improves the efficiency of the solar cell. Answer the following questions by giving qualitative arguments.

- a. Draw the band diagram without the i-region and label your sketch.
- b. Now, draw the band diagram with the i-region inserted between the p and the n side.
- c. For the band diagram in (b), sketch the charge distribution and electric field as a function of space.
- d. (\*) Using your band diagrams in (a) and (b), suggest a thickness for the i-region in the solar cell in order to obtain the biggest advantage in terms of improving the efficiency. Justify.
- e. Explain what will happen if the i-region was (i) very short or (ii) very long in the context of solar cells. (short and long is with reference to the length of the p and n junctions).
- f. In each of the two cases that you discussed in part (e), what will be the effective width of the depletion region as compared to that in part (a).

**17. (\*) Variable Doping:** In all the above cases, we have discussed constant (mostly) doping in the p and n sides of the junction. For this question, let the p-side have a constant doping,  $N_A$ . However, the n-side now has a linear doping, with a peak of  $N_D$  at the junction and linearly decaying to 0 at the end of the n-side (width,  $L_N$ ). Assume variable names wherever needed.

- a. Plot the charge distribution as a function of space.

- b. Plot the electric field and the potential as a function of space. Give functional form of the curve in your plot. (linear / quadratic / exponential, etc.)
- c. What advantage do you see, if any, in using a graded doping in p-n junctions?

**18. Heterojunctions:** Consider a p-i-n heterojunction (i smaller bandgap) and draw the band diagram at 0 V, forward and reverse bias.

**19. Currents in p-n junctions:** Consider a p-n homojunction made of Silicon with moderate doping on either side.

- a. Draw the steady-state band diagram at zero bias.
- b. Draw a typical I-V curve for this device.
- c. Now, consider that this device is transformed into a heterojunction with the n-side now being made of a material with a smaller band gap. Draw the steady-state band diagram at zero bias.
- d. (\*) For the device in (c), draw a typical I-V curve and mention the features by which it will differ from the curve that you drew in (b).
- e. Draw band diagrams for the device in (c) in forward and reverse bias.
- f. What applications/devices can you think of in which such a diode would be useful?

**20. Metal Semiconductor Junctions - An exercise in completeness:** Complete the following table with the type of contact (ohmic or schottky) that will be formed under the given conditions. For each case, illustrate with a band diagram at zero bias and justify your answer with one or two sentences. The symbols have their usual meaning.

	$\Phi_m > \Phi_s$	$\Phi_m < \Phi_s$
p-type semiconductor		
n-type semiconductor		

- a. Discuss the special case where  $\Phi_m = \Phi_s$ .
- b. Consider a schottky contact of your choice from the above table. Discuss what happens to this contact in terms of (i) barrier potential (ii) electrical conduction as you increase the doping from very low values to very high values.
- c. In the context of your answer to (b), is it possible to make an ohmic contact to any semiconductor through doping? Why or why not?

**21. Device engineer's DIY kit:** You have a certain tool box of metals and semiconductors whose material constants are given below. Answer the questions that follow using these values to support your arguments.

Metals (work function values in eV, in parenthesis):

Au (5.3), Ti (4.3), Cr (4.5), Ag (4.2), Ni (5.3), Zn (3.6), Al (4.1)

Semiconductors (electron affinity values in eV, in parenthesis):

Si (4.05), GaAs (4.07), AlAs (2.6), InAs (4.9), GaP (4.3)

Semiconductors (band gap values in eV, in parenthesis):

Si (1.1), GaAs (1.4), AlAs (2.16), InAs (0.36), GaP (2.2)

- a. What combination of metals and n-type semiconductors is guaranteed to give you a schottky contact irrespective of doping?

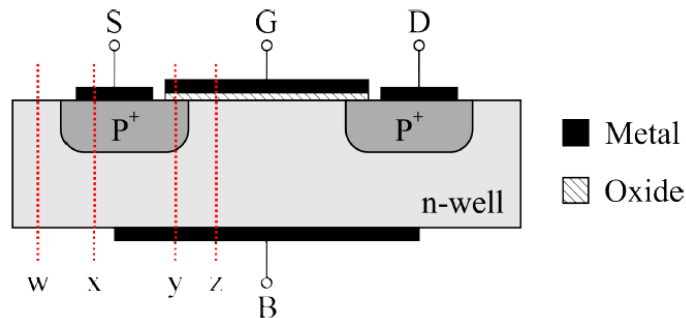
- b. What combination of metals and n-type semiconductors is guaranteed to give you an ohmic contact irrespective of doping?
- c. (\*) I need to decide the type of contact and the metals to deposit for each of the following applications. Reason out what metals you would choose.
  - (i) N-type GaP for a schottky diode.
  - (ii) P-GaAs for a laser.
  - (iii) N-Si for a solar cell.
- d. Under what conditions / situations would you want to use a schottky contact?

**22. Designing a solar cell:** You want to design a simple p-n junction LED. The device structure consists of a top contact / p-GaAs / n-GaAs / bottom contact.

- a. From your metals tool-box in the previous question, choose an appropriate contact for the top and the bottom of the solar cell. Justify your answer.
- b. Draw the band-diagram of the LED from the top contact to the bottom contact at zero bias.
- c. Draw the electric field and potential as a function of position in the entire device.
- d. Draw a schematic IV curve of this device and indicate where you would see light emission.
- e. (\*) Due to defects during deposition, the top contact is not ideal and displays a contact resistance of 1 kΩ. How will your answer to (d) change based on this new information. Plot the answers to (d) and (e) in the same figure to discern the difference.
- f. How will the 1 kΩ contact resistance affect the performance of the LED?

**23. Band diagrams galore:**

- a. For the PMOS device given below, draw the energy-band diagrams across the cross-sections w, x, y and z in both ON and OFF states.
- b. Now, consider the the gate oxide is not ideal and there are some trapped positive ions. How will this affect the performance of the device? Discuss with reference to the threshold voltage.



**24. Effect of back-gate on MOS devices:** Consider an NMOS device.

- a. Sketch a typical  $I_D$  vs  $V_G$  curve for the device above, noting its essential features and the threshold voltage. Do not worry about the back gate. Yet.
- b. Sketch a typical transfer characteristics curve for different values of the gate voltage.
- c. (\*) Discuss, in physical terms (electrons, currents and voltages), what happens under the following conditions (Assume that the source contact is grounded).
  - (i) For a constant gate bias, how does threshold voltage change with the back gate? Discuss both positive and negative back gate bias. In the literature, this is often called the body effect or the back-gate effect.

- (ii) Assume that the device is currently in the ON state at a certain gate voltage  $V_G$  and drain voltage  $V_D$ . Discuss how is the current in the channel ( $I_D$ ) change with back gate voltage? Go from a very large negative bias to a very large positive bias discussing all 'interesting' conditions.

**25. (\*) Short channel effects in a MOSFET:** For this question, you only need to know about p-n junction concepts to understand the secondary effects in a MOSFET. In addition to the standard NMOS operation, the n-type source and drain regions are in contact with the p-type substrate, creating depletion regions around these junctions. We usually ignore this because the junction width is much smaller than the channel length. In this problem, we will consider an NMOS structure with a short channel length, and so we cannot ignore the depletion regions formed between the source and drain regions with the substrate. Assume the MOSFET is in saturation regime and the source is grounded.

- What does it mean for a MOSFET to be in saturation, in terms of the gate and drain bias?
- To generate a current through the NMOS device, the drain has to be positively biased. However, this puts the drain-substrate junction in reverse bias. The higher the drain voltage (to increase drain current), the higher the reverse bias between the drain and the substrate. With a short channel length, explain how increasing the drain voltage affects the threshold voltage of the MOSFET? This is often called Drain Induced Barrier Lowering (DIBL) in short channel MOSFETs.
- Up until now, we have ignored the depletion region that is present around the source-substrate junction. With increasing drain voltage, the depletion region around the drain-substrate junction keeps growing. Subsequently, with a high enough drain voltage, you can think of a situation where the depletion regions of the drain-substrate junction merges with the source-substrate junction. Explain what will happen to the device performance in this case in terms of the threshold voltage and drain current? This phenomenon is referred to as 'punch-through'.
- In the linear region of operation, we assumed that increasing the drain voltage increase the current in the channel. This however assumes that the electron velocity scales linearly with electric field. Explain what would happen with increasing drain voltage once saturation velocity is reached?

**26. Bipolar Junction Transistors:** Draw the flat band energy diagram for a common-base NPN bipolar transistor in the following regimes of operation.

Indicate if there is a current flowing through the device in each case and if yes, between which terminals.

- Forward active: (Base-emitter forward bias, Base-collector reverse bias)
- Cut-off: (Base-emitter reverse bias, Base-collector reverse bias)
- Reverse-active: (Base-emitter reverse bias, Base-Collector forward bias)
- Saturation (Base-emitter forward bias, Base-collector forward bias)

How would the bias change in the case of a PNP bipolar transistor to achieve the same functional output as the four regimes of operation state above?

**27. Hypothetical FET type devices:**

- a. Consider a device similar to an n-MOSFET, except that there is no oxide. So, you have n-doped source and drain in a p-doped substrate. A metal contact is deposited just above the channel region without any oxide layer. Answer the following questions qualitatively. You can use band diagrams to better illustrate your answers.
- (i) Will you have a 'threshold voltage' for this device? If no, why not? If yes, what would it physically correspond to in the device?
  - (ii) Assume that the drain has a small positive bias to collect current. Draw the  $V_G - I_D$  characteristics for this hypothetical device. Explain what the 'gate voltage' does in this case (both positive and negative  $V_G$ ).
  - (iii) Do you see a 'field-effect' behavior in this device as in a conventional MOSFET?
  - (iv) Can you operate this hypothetical device in 'inversion' mode? Why or Why not?
  - (v) Draw the transfer characteristics ( $I_D - V_D$ ) for different 'gate' voltages. Explain your plot with references to the difference from a conventional MOSFET.
  - (vi) What is the device that you've studied that closely resembles this device?
- b. Consider a hypothetical semiconductor-oxide-semiconductor device (SOS). This is very similar to an n-MOSFET, except that you now have an n-type semiconductor on top of the oxide instead of a metal. Give qualitative answers, supporting it with band diagrams wherever necessary.
- (i) Draw the band diagram across the SOS interface at zero bias.
  - (ii) How will you define a threshold voltage for this device?
  - (iii) How will the threshold voltage of this device compare to that of a conventional n-MOSFET, given all identical device parameters.
  - (iv) Explain the concept of accumulation, depletion and inversion in this structure using band diagrams and point out how this is different from a conventional MOSFET.
  - (v) Draw the  $I_D - V_G$  characteristics of this device. Again, discuss why and how this is different from conventional MOSFET curves.
  - (vi) Draw the transfer characteristics ( $I_D - V_D$ ) for different 'gate' voltages. Explain your plot with references to the difference from a conventional MOSFET.
  - (vii) What is the device that you've studied that closely resembles this device?