Version B
Mark B for Q50 in the bubble sheet

RYERSON UNIVERSITY
Department of Physics
PCS 224 – Solid state physics

Please Print:

Student:_______________________________ _____________________________
Last Name *First Name*

Student Number: ______________________ Student Section #: ________________
(check your bubble sheet for section #)

Final Exam – Dec 4, 2019

INSTRUCTIONS

1. **Duration of the test: 180 minutes**
2. The total number of points is 100 points.
3. This is a closed-book exam; pens, pencils, erasers, calculators and your Ryerson ID are the only allowed items on your desk. Your Ryerson photo ID must be on your desk at all times.
4. Check that the “bubble sheet” at your desk has your name and student number on it.
5. The only calculators allowed are the Sharp EL-546 and Casio FX-991**.**
6. Coats, jackets, caps and bags must be placed out of reach.
7. We may check your work, and if your answer is not justified by it, credit will not be given. You may use the back of the pages for rough work.
8. **Select the option that is closest to your answer for the multiple-choice questions**, circle it in this booklet, then copy it to the bubble sheet carefully using a pencil.

Please sign here indicating you have read and understood the above instructions.

Signature: ____

DO NOT OPEN THE EXAM UNTIL YOU ARE TOLD TO DO SO
Then, before you start writing, verify that you **do** have all 16 pages without including the formula sheets (otherwise inform one of the invigilators). **You can separate the formula sheets from the booklet.**

[This page is intentionally blank and can be used for calculations]

Multiple Choice (4 points each for a total of 60 points)

1. You would like to increase the resistivity of a certain intrinsic semiconductor. What can you do to accomplish this?
   a. Apply an electric current to the semiconductor
   b. Introduce donor impurities
   c. Introduce acceptor impurities
   d. Increase the temperature
   e. Decrease the temperature

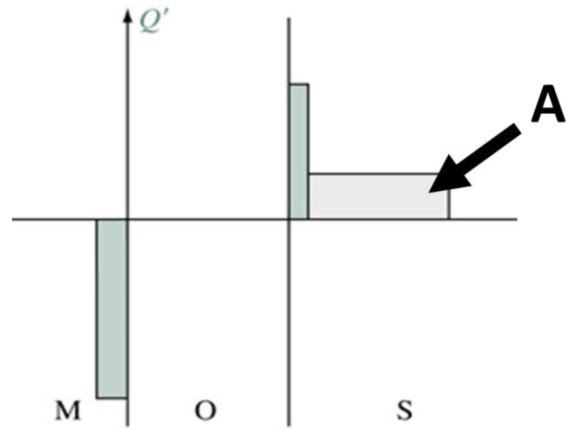
2. A Silicon semiconductor has had one out of every 10^7 silicon atoms replaced with a donor atom. How far above the top of the valence band is the Fermi energy? [Take all relevant data for Silicon from the table on the equation sheet].

   a. The Fermi energy is below the top of the valence band.
   b. 1.12 eV
   c. 0.86 eV
   d. 0.56 eV
   e. 0.21 eV

The following TWO problems refer to the charge diagram shown

3. The rectangle on the right side of the diagram (labeled “A”) contains which kind of charges?

- **a.** Holes
- **b.** Electrons
- **c.** Donor ions
- **d.** Metal ions
- **e.** Acceptor ions



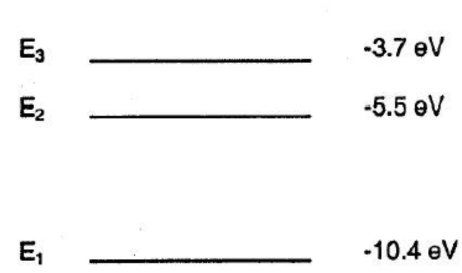
4. The charge diagram at the right is representing:

- **a.** PMOS in the inversion mode.
- **b.** NMOS in the accumulation mode.
- **c.** PMOS in the depletion mode.
- **d.** NMOS in the inversion mode.
- **e.** NMOS in the depletion mode.

5. Flatband voltage of a MOSFET is

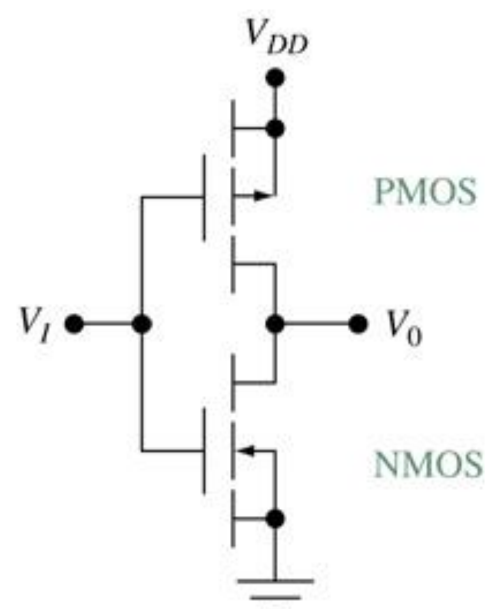
- **a.** The gate voltage which is the boundary between depletion and inversion modes.
- **b.** The gate voltage at which the MOSFET turns off.
- **c.** The gate voltage at which the surface potential is zero.
- **d.** The drain/source voltage at which the channel starts to form.
- **e.** The drain/source voltage at which the channel starts to disappear.

6. A fictitious atom X (NOT hydrogen) has energy level diagram shown. Assume that these are the ONLY three state available to this atom's electron. A gas of these "X" atoms is put into a tube and an electrical current is passed through the tube, exciting the electrons to the higher states. Light is emitted as electrons transition between these three states. What is the **longest** wavelength of light can be emitted from this system?



   a. 959nm
   b. 689nm
   c. 253nm
   d. 185nm
   e. 119nm

7. Consider the CMOS inverter shown.
   V_{TN} =+1.0 V, V_{TP}= −1.0V, V_{DD}= +3.0 V. When V_I =+2.5 V,



   a. PMOS is off, NMOS off.
   b. PMOS is on, NMOS off.
   c. PMOS is off, NMOS on.
   d. PMOS is on, NMOS on.
   e. The answer cannot be determined without knowing V_0.

8. Light from a source with a variable frequency is incident on a photoelectric apparatus. By smoothly changing the light's frequency, it is found that light with wavelength longer than λ_c does not release electrons. If ϕ is the work function of the metal, determine the stopping voltage when the incident light has wavelength $\lambda_c/4$.

   a. $4\,\phi/e$
   b. $3\phi/e$
   c. $2\phi/e$
   d. ϕ/e
   e. No electrons will be emitted with this incident wavelength

9. At room temperature, a diode is forward biased with a voltage of +0.1V. The leads are then switched and the diode is reverse biased with a voltage of -0.1V. How many times larger is the forward bias current than the reverse bias current?
   a. Infinitely large (no current flows in a reverse biased diode)
   b. Twice as large
   c. They are equal
   d. About 50 times larger
   e. About 200 times larger

10. A MOSFET device is created using a silicon substrate with $N_a = 3 \times 10^{14}\mathrm{cm}^{-3}$. For a particular applied gate voltage, the density of exposed charges in the depletion region is $3.94 \times 10^{10}\mathrm{e/cm}^2$. Determine the surface potential

- **a.** $+0.51$ V
- **b.** $+0.40$ V
- **c.** $+0.26$ V
- **d.** -0.26 V
- **e.** -0.51 V

11. Which of the following statement(s) are true for a biased p-n junction?

- **a.** When the junction is reverse biased, the width of the depletion region increases from its unbiased value.
- **b.** When the junction is forward biased, the magnitude of the net electric field in the depletion region decreases from its unbiased value
- **c.** For a p-n junction to be reverse biased, the positive terminal of the power supply should be connected to the n-side
- **d.** Both (a) and (b) are true, but not (c)
- **e.** All three (a), (b), and (c) are true.

12. Which of the following statements is **NOT** true?

   a. A photodetector operates under reverse bias
   b. The energy of photons emitted by an LED depends on the bandgap of its semiconductor material.
   c. When light shines on a photoconductor, the conductivity of the material increases.
   d. The output power of a solar cell does not depend on the resistor which is connected
   e. A solar cell's short circuit current depends only on the light intensity

13. In a particular p-n junction, 2/3 of the depletion region lies on the p-side of the junction. How do the doping concentrations on each side compare?

   a. $2N_d = 3N_a$
   b. $N_d = 2\ N_a$
   c. $N_a = 3\ N_d$
   d. $N_a = 2\ N_d$
   e. $3N_d = 2N_a$

14. An enhancement type NMOS is in depletion mode at $V_{GS} = 0$. What can you say about the flatband and threshold voltages of this device?

- **a.** The flatband voltage is negative and the threshold voltage is positive
- **b.** The flatband voltage is positive and the threshold voltage is positive
- **c.** The flatband voltage is negative and the threshold voltage is negative
- **d.** The flatband voltage is positive and the threshold voltage is negative
- **e.** There is not sufficient information to make any conclusion about the sign of these voltages

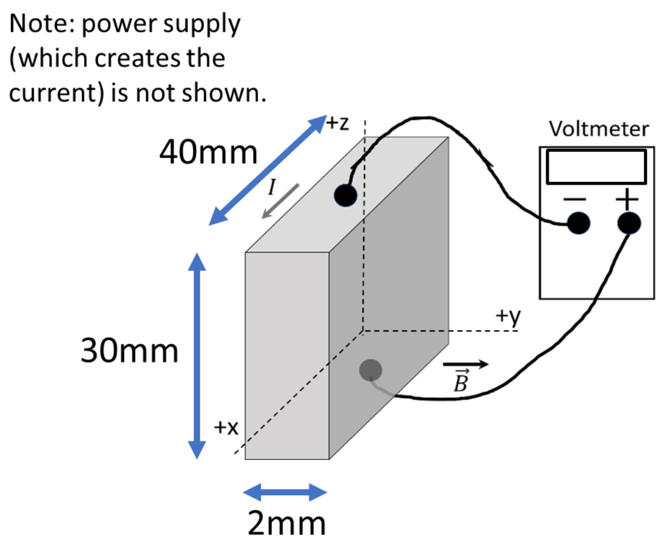
15. A 2.0mW red laser is shined on a metal and as a result, electrons are released from the metal. Now the red laser is replaced with a 2.0mW blue laser (blue light has a higher frequency and shorter wavelength than red light), which now shines on the same metal. Compare the number of electrons released per second, as well as their maximum kinetic energy in these two situations.

The blue laser releases ________________

- **a.** **The same** number of electrons per second, but each one has a **higher** maximum kinetic energy than with the red laser
- **b.** **Less** electrons per second, but each one has **the same** maximum kinetic energy as with the red laser.
- **c.** **Less** electrons per second, each one has a **higher** maximum kinetic energy than with the red laser
- **d.** **More** electrons per second, but each one has a **lower** maximum kinetic energy as with the red laser
- **e.** **More** electrons per second, and each one has **a higher** maximum kinetic energy

Full Answer Questions (40 pts total) – <u>All work must be shown.</u> Your solution must be clear and readable in order to receive full marks

1.) (13 pts) A strongly doped silicon semiconductor is used in a Hall Effect experiment with the parameters shown.



Conventional Current **I**	Magnetic field	Dimensions x × y × z	Hall Electric Field (V/cm)	Voltmeter Reading	Carrier charge	Carrier density (cm^{-3})
30 mA in +x direction	______ in +y direction	40mm×2mm×30mm	0.12 in −z direction			2.5×10^{13}

a. **(3 pts)** Determine the reading on the voltmeter. Be sure to indicate whether it will be positive or negative.

b. **(2 pts)** Determine the type of the semiconductor (n-type or p-type). Explain your reasoning.

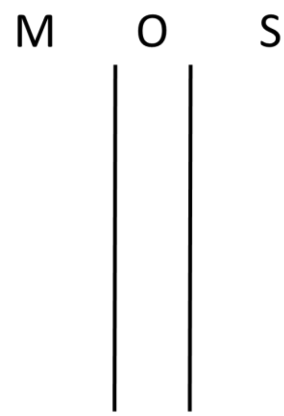
c. **(3 pts)** Determine the magnitude of the magnetic field (in units of Tesla)

For parts (d) and (e), suppose that the experimental setup stays **exactly the same**, except now a current of 30mA is passed in the $+y$ direction **instead** of the $+x$ direction.

d. **(3 pts)** What **power supply voltage** will be necessary to create a current of 30mA in the +y direction?

e. **(2 pts)** What will the voltmeter shown in the diagram read now that the current is flowing in the +y direction?

2.) (4 pts) Draw the **energy level** diagram for a PMOS in depletion mode on the figure. Label all relevant energy levels



3.) (12 pts) A silicon p-n junction has a built-in potential of 0.580V and the device is at room temperature. The electron concentration on one side of the junction is $4.5 \times 10^{14}\mathrm{cm}^{-3}$.

a. **(5 pts)** Determine the **electron** concentration on the other side of the junction.[1]

[1] The problem continues on the next page

b. **(5 pts)** This p-n junction is now used as a photodetector. Incoming light creates an electron/hole pair at the exact center of the junction. Immediately after they are created, the electron feels a force with magnitude 3.04×10^{-13} N. What reverse bias voltage is being used to operate the photodetector? [Ignore the attractive force the electron and the hole exert on each other.]

c. **(2 pts)** Which wavelengths of light can this photodetector detect? Give your answer as a range of wavelengths.

4.) (11 pts) A certain MOSFET has threshold voltage -1.5V. The substrate of the MOS is silicon, has an impurity concentration 10^{16}cm^{-3} and a metal-semiconductor work function -1.1V. The oxide is silicon-dioxide with a dielectric constant 3.9 and thickness $2.25 \times 10^{-6}\text{cm}$. The oxide has a trapped charge density $1.34 \times 10^{12}\text{e/cm}^2$.

a. **(1 pt)** Determine the material from which the gate is made. (No explanation necessary)

b. **(4 pts)** Classify this MOSFET as enhancement/depletion type and PMOS/NMOS. Explain your reasoning.

c. For a particular gate voltage it is found that when V_{DS} > 0.5V, the current no longer increases but remains constant at 16mA.

i. **(2 pts)** What was the value of the gate voltage?

ii. **(4 pts)** If instead the MOS is biased with $V_{GS} = +1.5\text{V}, V_{DS} = +4.0V$, what current will flow?

<u>**This is version B – Please mark Q#50 of your Bubble Sheet with B**</u>

THE END

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