1. (5 pts) Consider a metal-oxide-semiconductor sandwich such as you would find in an MOS transistor. The semiconductor is P type with an acceptor density, $N_A = 10^{16}/\text{cm}^3$. Sketch the charge density, qualitatively to scale, as a function of depth for 3 cases, (i.e. with the horizontal (depth) axis aligned with the device.). Ignore what happens at the contacts, A and B.

a) a relatively low positive voltage applied to the contact A.
b) a relatively high (above threshold) positive voltage applied to the contact A.
c) a relatively low negative voltage applied to the contact A.
d)-f) next page
Now consider the case of the semiconductor oxide semiconductor sandwich, note the different doping density.

- d) a relatively low positive voltage applied to the contact A.
- e) a relatively low negative voltage applied to the contact A.
- f) a relatively high negative voltage applied to the contact A.
2. (5 points) Suppose you have an MOS transistor

a) The threshold voltage is 2V. The gate, G, is connected to the drain, D. Sketch, with qualitatively correct shape the I-V characteristic, namely the drain-source current versus the drain-source voltage. You can assume B is connected to S. Indicate explicitly specific points on the horizontal axis of the plot.
b) Consider the case: G is not connected to D, S is connected to B, Under what conditions is the low frequency or static capacitance from G to B equal to $\varepsilon_{ox}A/d$? $\varepsilon_{ox}$ is the dielectric constant of the oxide, A is the area of the gate, and d is the thickness of the oxide. Under what conditions is it not equal to $\varepsilon_{ox}A/d$?

c) If the doping concentration of the p-type substrate is increased does the threshold voltage go up or down? Explain.
3). (5 points)  a) Suppose you have an n-type Si sample with \( n_o \) electrons/cm\(^3\). Suppose it is uniformly illuminated to create electron-hole pairs at a constant density throughout the sample, such that the electron density becomes \( n_o + n' \) and the hole density becomes \( p_o + p' \) where \( n' = p' \). Assume \( n' \ll n_o \). Suppose at time \( t = 0 \) the illumination is turned off. Write an expression for the hole concentration, \( p' \), as a function of time.

b) Suppose you are continuously and uniformly illuminating only half of the sample, i.e. for \( x < 0 \) in the drawing. Otherwise the conditions are the same as in part a). Sketch the dependence of \( p' \) on \( x \) throughout the sample. Assume the sample is long, i.e. don’t consider end effects.
4) (5 points) a) Derive an expression for the resistance from the end to end i.e. from A to B of a slab of material of width “w”, length “l” and thickness “a”. The material has a resistivity, ρ, which is a function of depth x, i.e ρ = ρ(x). (note if you apply a voltage from A to B to measure the resistance, the electric field will be uniform in x & y and will vary only in z)

b) This kind of consideration is important in practice for example if dopant is diffused in to a silicon surface and the donor density is a function of depth. For example: N_D = N_0 exp(-x/L_D). The mobility is μ. Note that conductivity, σ = 1/ρ, is proportional to N_D. Consider that a >> L_D. Derive an expression for the resistance of the slab in this case.
2. a) The curve looks like a diode characteristic with forward current beginning to increase at 2 volts.

b) The capacitance is equal to $\varepsilon_{ox}A/d$ either when the device is on and there is an inversion layer below the oxide ($V_{GS}$ above 2 volts) (If B is not connected to S, the depletion capacitance is then in series with the oxide capacitance.) or when the gate voltage is sufficiently negative (below flat band) to form an accumulation layer below the oxide.

c) The threshold voltage will go up. The voltage needed to invert the surface will be higher. The threshold voltage is the sum of three terms: the flat band voltage, the potential in the p region ($\sim \ln N_A$), and the charge term proportional to $\sqrt{N_A}$. Both of the terms increase the threshold voltage.
3. a) \[ p(t) = p' \exp(-t/\tau) \]

4. a) A slice of thickness \( dx \) will conduct a current \( \Delta I \).

\[ \Delta I = \frac{V W}{\mu(x) l} \Rightarrow I = \int_0^a dx \frac{V W}{I \mu(x)} \]

\[ R = \frac{V}{I} = \frac{e}{W} \int_0^a dx \frac{1}{\mu(x)} \]

b) \[ \sigma = N_e \mu = \mu N_0 \exp \left( -\frac{x}{\lambda} \right) = \frac{1}{\mu(x)} \]

\[ R = \frac{e}{W} \frac{1}{\mu N_0} \int_0^a dx \exp \left( -\frac{x}{\lambda} \right) \]

\[ R = \frac{e}{W} \mu N_0 \lambda \left( 1 - e^{\frac{-a}{\lambda}} \right) \approx \frac{e}{W\mu N_0} \lambda \]

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