UNIVERSITY OF CALIFORNIA

College of Engineering
Department of Electrical Engineering
and Computer Sciences

Professor Oldham Spring 1999

# EECS 105 — Midterm 1

Thursday, 25 February 1999

**Your name:** ________________ ______________________
first last

**Your discussion TA:** ☐ Allan Chang ☐ Lily Tam

- This is a closed book exam, but you may use your page of notes.
- Please do all your work on the pages of this exam. Ask if you need extra paper.
- Full credit will be given only when you indicate the source of your answer, such as a table, graph, or calculation.
- Please write your name in the above space
- Special notes:

1. SOME GRAPHS AND FORMULAS ARE GIVEN AS APPENDICES TO THIS EXAM. BE SURE TO LOOK THESE OVER.
   ☐ Yes, I have looked these over. (Check box)
2. SOME PARTS OF THE EXAM ARE GRADED WITH NO PARTIAL CREDIT. They are noted. You may wish to double check your answers on those parts.
3. ONCE IN A WHILE SOME EXTRA CREDIT IS POSSIBLE FOR CLEVER INSIGHT. Again, these places are noted. But we will not answer questions about these problems. Just be very clear in your work.

| | **SCORE** |
|---|---|
| Problem 1 (20 pts.) | |
| Problem 2 (25 pts.) | |
| Problem 3 (30 pts.) | |
| Problem 4 (25 pts.) | |
| **TOTAL** (100 pts.) | |

## Problem 1 (20 pts.)

**a.** [No partial credit] In a certain process, a $2\mu\text{m}$ thick layer of n-type silicon (doping = $2 \times 10^{15}/\text{cm}^3$ is created over a p-type substrate. It is to be used for the purpose of making integrated circuit resistors. What is the sheet resistance of this layer? (Units must be $\Omega/\text{square}$.)

____________

**b.** Using the layers of (a), above, you need to make a resistor with value of $200K\Omega$. It is $5\mu\text{m}$ wide. What must its length be (ignoring contact effects)?

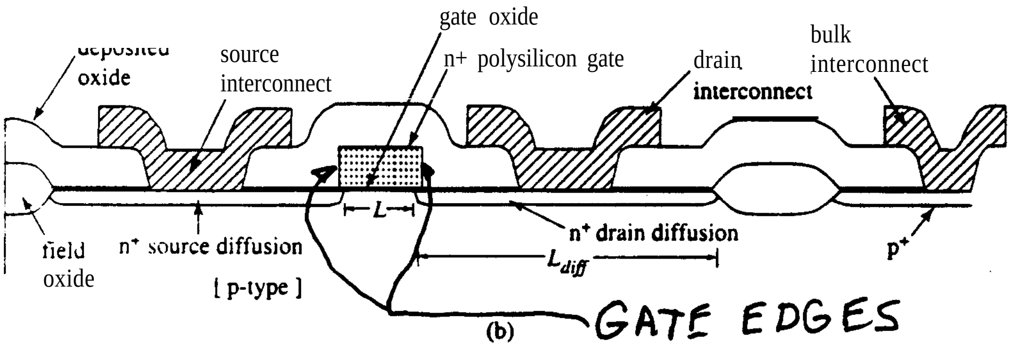
____________

**c.** Someone properly points out to you that the layer in part a), though it is physically $2\mu\text{m}$ thick, is electrically somewhat thinner, because there must be a depletion layer at the n-p interface. (You are to ignore this in part a.) Suppose the doping in the p region is also $2 \times 10^{15}/\text{cm}^3$ (but acceptors instead of donors). At zero applied voltage between the n and p regions (i.e., in thermal equilibrium), just what is the net electrical thickness of the n-region? (Thickness minus depleted portion.)

____________ $(\mu\text{m})$

## Problem 2 (25 points)

The structure below is made with 4 masking steps.



Four-mask layout and cross section **of an integrated n-channel MOSFET.**

a. Name the masks (use the terminology within the figure in the names, if possible).

**b.** For each mask name point to two edges in the cross-section which come about as a result of the application of that mask (photolithography and etching.) The gate edges are identified as an example.

c. If this structure represents the n-mos transistor in my **450MHz** pentium processor (made with a so-called "quarter-micron process," can you give me approximate values for the size of the following:

**c.1)** $L$ ____________

c.2) $L_{diff}$ ____________

c.3) gate oxide thickness ____________

c.4) metal thickness ____________

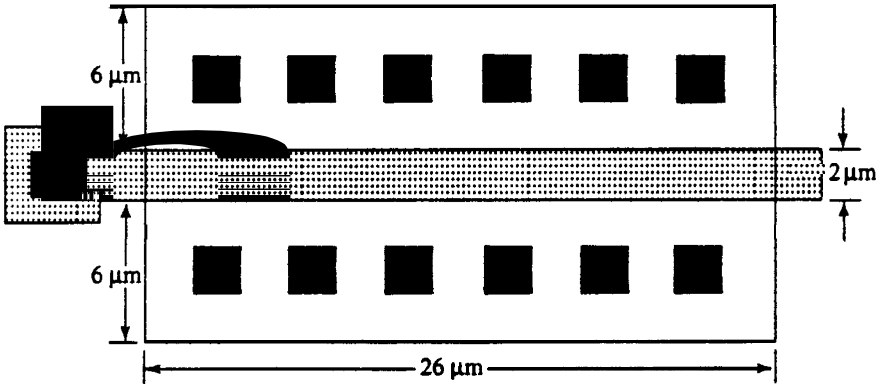
**c.5)** $n^+$ layer thickness ____________

d. Why is $L_{diff}$ so much bigger than $L$? Is this not wasted space? [Extra credit possible]

e. If this is an n-channel MOS transistor, what is the purpose of the **$p^+$ region?**

## Problem 3 (30 points)

An MOS structure is made with the layout



The cross-section is the same as the left-hand part of the figure in Prob. 2.

The substrate is doped $2 \times 10^{15}/\text{cm}^3$ with acceptors and the gate oxide is 40nm thick.

a. [No partial credit] What is the flat-band voltage $V_{FB}$?

____________

b. [No partial credit] What is the capacitance of the gate to substrate for $V_{SB} = 0$ and $V_{GS} < V_{FB}$? (Ignore overlap and other second order effects.)

____________ **(pF)**

c. What is the Threshold voltage $V_{Tn}$?

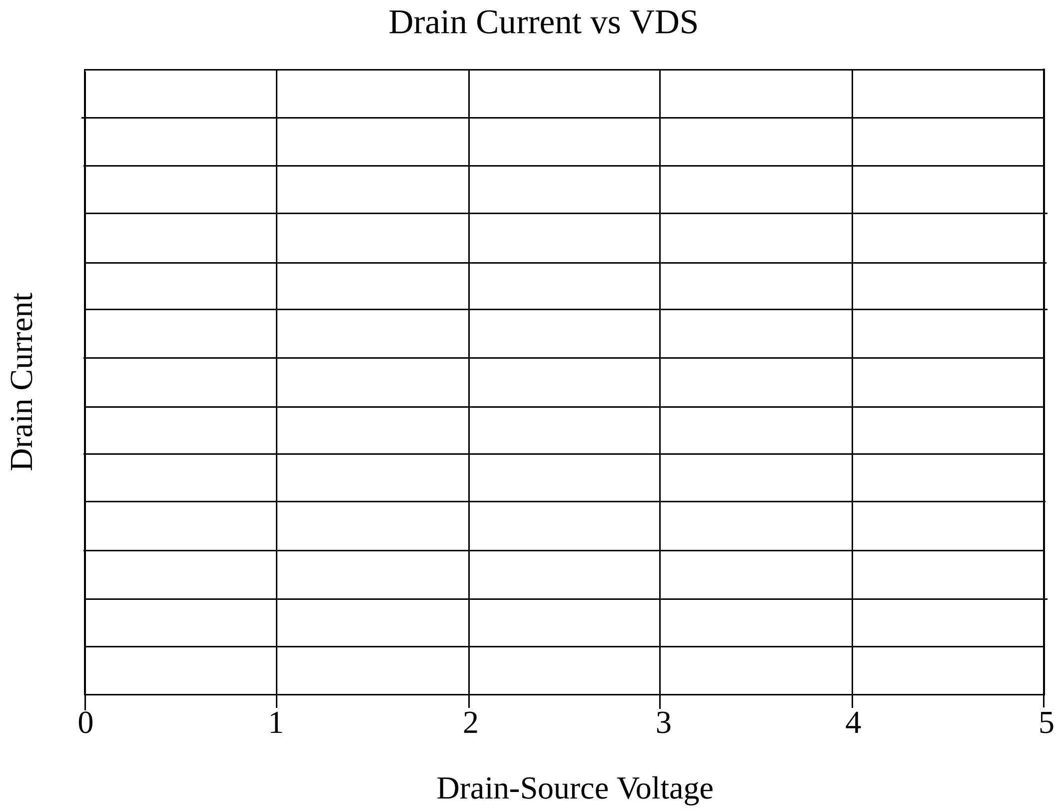
____________V

**d.** Now we adjust the flat-band voltage (and thus the threshold voltage) with an ion implant just at the bottom of the gate oxide. We set the implant value to get a final threshold $V_{Tn}$ of 0.5 V. In testing the device we short source to body, i.e., $V_{SB} = 0$.

**d.1)** [No partial credit] What is $V_{DSAT}$ of this device if we set $V_{GS} = 2\text{ V}$?

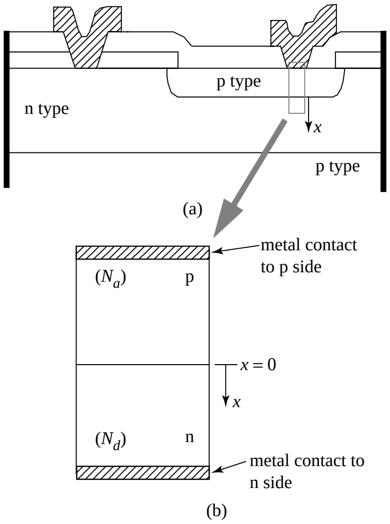
______________

**d.2)** Neatly sketch the I-V characteristics on the linear axes below for three cases: $V_{GS} = 0.5\text{ V}$, $V_{GS} = 1\text{ V}$, and $V_{GS} = 2\text{ V}$. Cover the range $V_{DS} = 0$ to $5\text{ V}$. Assume the electron mobility in the channel is $500\ \text{cm}^2/\text{Vsec}$. You must put a scale on the current axis. (Note that partial credit will only be possible if you very carefully show your work, including giving any formulas you are using before evaluation.)



## Problem 4 (25 points)

A p-n junction capacitor is made in an integrated circuit with the cross-section as shown below. The p-region is very heavily doped compared to the n-region (it is a $p^+n$ junction) and the n-region doping is $1 \times 10^{14} / \text{cm}^3$. The junction area is $100 \times 200 \mu\text{m}$, or $2 \times 10^{-4}\ \text{cm}^2$.



**a)** Make a sketch of the charge density $\rho$ (C/cm$^3$), the electric field $E$ (V/cm), and the potential $\phi$ versus $x$ for this structure at 5V reverse bias. The "graph paper" is provided on the page opposite. As part of the calculation to prepare these graphs, please compute the following:

**a.1)** The built in voltage

____________(V)

**a.2)** The depletion width at 5V reverse bias

____________($\mu$m)

**a.3)** The peak electric field at 5V reverse bias

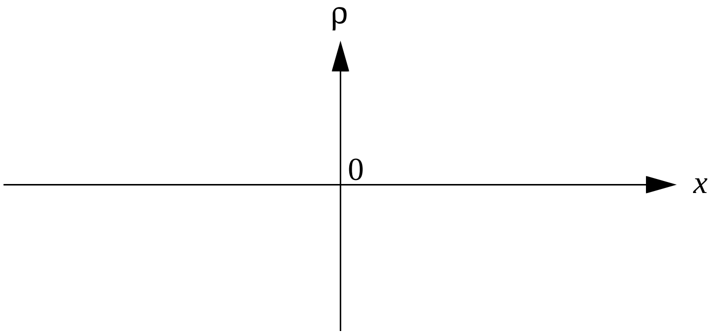
____________(V/cm)

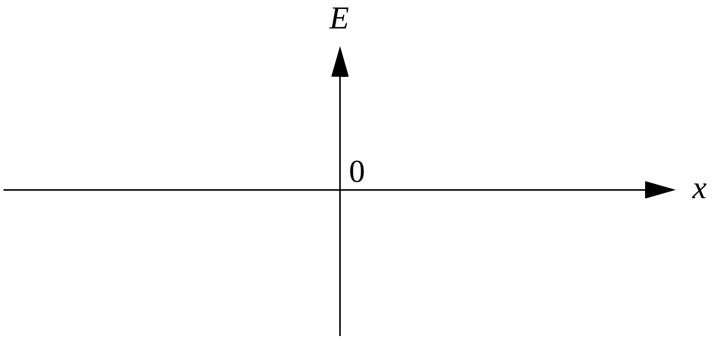
**b)** What is the small-signal capacitance at 5V reverse bias?

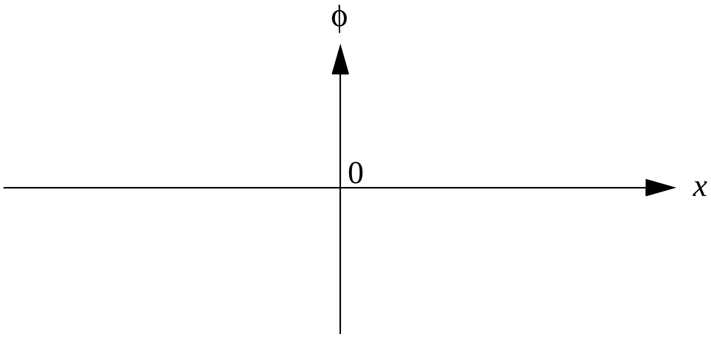
Formula (in terms of known quantities) ____________F

Value ____________pF

**Prob. 4 (cont.)**







**c)** The n-region ends in an ohmic contact at $x = 15\mu\text{m}$. Taking into account the answer to part a.2, calculate the current at 0.7V forward bias.

**c.1)** First give the formula for the current in terms of doping, geometry, etc. (All must be known quantities.)

______________ A

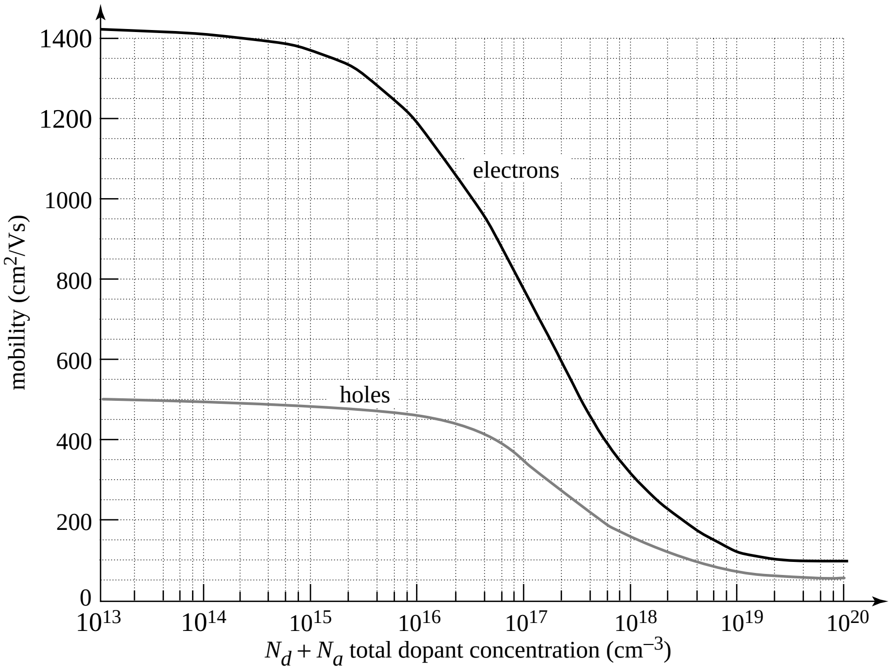
**c.2)** List the values of all the quantities in the formula above

______________ ______________ ______________ ______________ ______________

**c.3)** Evaluate the current

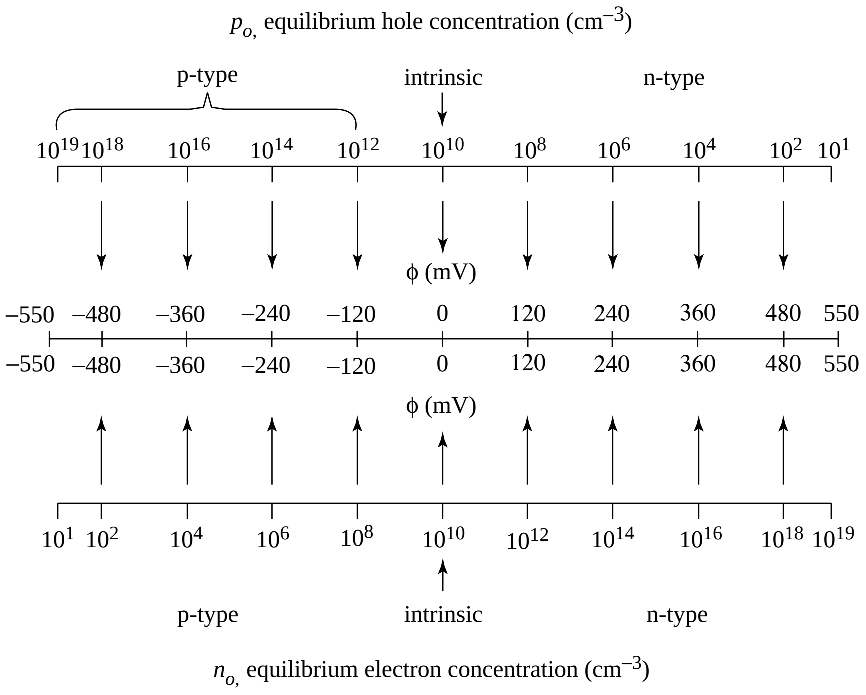
______________ μA

# Appendix A:



Log-linear plot of electron and hole mobilities at room temperature, as functions of the total doping concentration $N_d + N_a$. Note that electron and hole diffusivities are given by: $D = kT/q\mu$.

# Appendix B:



# Appendix C: Formulas

**(EQ 2.7)** $n_o \cdot p_o = n_i^2(T)$

**(EQ 2.34)** $v_{dn} = -\mu_n E$

**(EQ 2.55)** $J_n = J_n^{dr} + J_n^{diff} = qn\mu_n E + qD_n \frac{dn}{dx}$

**(EQ 2.56)** $J_p = J_p^{dr} + J_p^{diff} = qp\mu_p E - qD_p \frac{dp}{dx}$

**(EQ 2.67)** $R = \left(\frac{1}{qN_d\mu_n t}\right)\left(\frac{L}{W}\right) = R_{\square}\left(\frac{L}{W}\right) = R_{\square}N_{\square}$

**(EQ 3.1)** $\frac{dE}{dx} = \frac{\rho}{\varepsilon}$

**(EQ 3.4)** $E(x) = -\frac{d\phi(x)}{dx}$

**(EQ 3.56)** $X_{do} = x_{no} + x_{po} = \sqrt{\left(\frac{2\varepsilon_s\phi_B}{q}\right)\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}$

**(EQ 3.88)** $V_{FB} = -(\phi_{n+} - \phi_p)$

**(EQ 3.89)** $Q_G(V_{GB} = V_{FB}) = 0$

**(EQ 3.95)** $V_{Tn} = V_{FB} - 2\phi_p + \frac{1}{C_{ox}}\sqrt{2q\varepsilon_s N_a(-2\phi_p)}$

**(EQ 4.18)** $V_{DS_{SAT}} = V_{GS} - V_{Tn}$

**(EQ 4.19)** $I_{D_{SAT}} = \left(\frac{W}{2L}\right)\mu_n C_{ox}(V_{GS} - V_{Tn})^2 = \left(\frac{W}{2L}\right)\mu_n C_{ox}V_{DS_{SAT}}^2$

**(EQ 4.59)**

$$I_D = 0 \text{ A} \qquad (V_{GS} \le V_{Tn})$$

$$I_D = (W/L)\mu_n C_{ox}[V_{GS} - V_{Tn} - (V_{DS}/2)](1 + \lambda_n V_{DS})V_{DS} \qquad (V_{GS} \ge V_{Tn}, V_{DS} \le V_{GS} - V_{Tn})$$

$$I_{D_{SAT}} = (W/2L)\mu_n C_{ox}(V_{GS} - V_{Tn})^2(1 + \lambda_n V_{DS}) \qquad (V_{GS} \ge V_{Tn}, V_{DS} \ge V_{GS} - V_{Tn})$$

**(EQ 4.60)** $V_{Tn} = V_{TOn} + \gamma_n(\sqrt{-V_{BS} - 2\phi_p} - \sqrt{-2\phi_p})$

**(EQ 4.67)** $g_m \cong \left(\frac{W}{L}\right)\mu_n C_{ox}(V_{GS} - V_{Tn}) = \sqrt{2\left(\frac{W}{L}\right)\mu_n C_{ox} I_D}$

**(EQ 6.10)** $$\phi_B = V_{th}\ln\left(\frac{p_{po}}{p_{no}}\right) \text{ and } \phi_B = V_{th}\ln\left(\frac{n_{no}}{n_{po}}\right)$$

**(EQ 6.22)** $$p_n(x_n) = p_{no} \cdot e^{V_D/V_{th}} \text{ and } n_p(-x_p) = n_{po}e^{V_D/V_{th}}$$

**(EQ 6.30)** $$J = qn_i^2\left(\frac{D_p}{N_dW_n} + \frac{D_n}{N_aW_p}\right)(e^{V_D/V_{th}} - 1)$$

**(EQ 6.31)** $$I_D = qn_i^2A\left(\frac{D_p}{N_dW_n} + \frac{D_n}{N_aW_p}\right)(e^{V_D/V_{th}} - 1) = I_o(e^{V_D/V_{th}} - 1)$$

**(EQ 6.48)** $$C_j = \frac{C_{jo}}{\sqrt{1 - V_D/\phi_B}}$$

## Appendix D: Values

$$q = 1.6 \times 10^{-19} C$$

$$V_t = kT/q = 0.026 \text{ V}$$

$$\varepsilon_0 = 8.85 \times 10^{-14} \text{ F/cm}$$

$$\varepsilon_{\text{oxide}} = 3.9\varepsilon_0$$

$$\varepsilon_{Si} = 11.7\varepsilon_0$$