Mid-term examination

Sung-Min Hong (smhong@gist.ac.kr)

Semiconductor Device Simulation Lab.

School of Information and Communications

Gwangju Institute of Science and Technology

Welcome!

- Total nineteen (19) problems
  - Five (5) minutes for each problem
  - 95 minutes long

- Policy
  - No cellphone!
  - No calculator!
  - No question!

- Recommendation
  - Prepare your answer sheets. (Write down your name.)

If not otherwise stated,

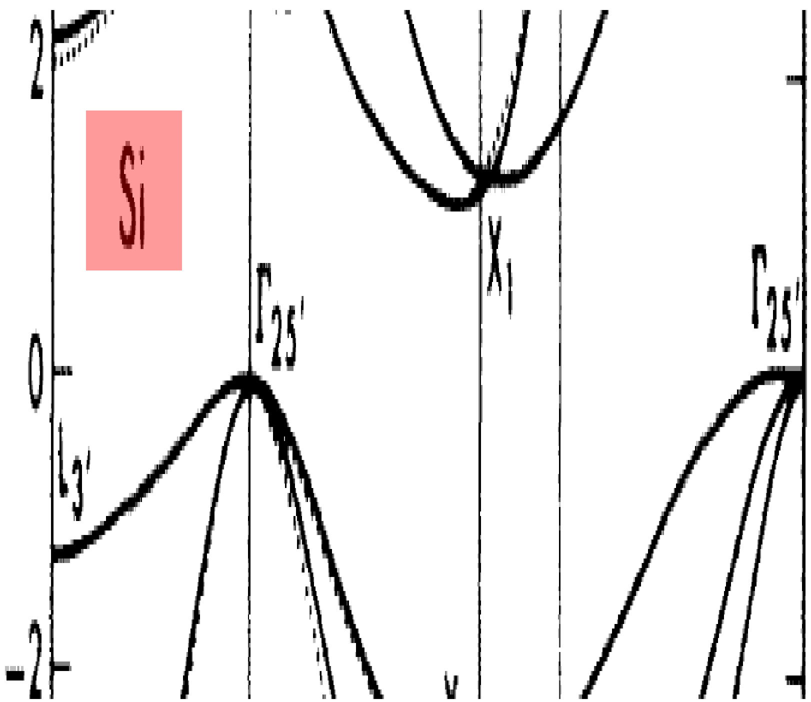
- Assume that following conditions:
  - 300 K
  - Silicon

- For MOSFETs,
  - NMOSFET
  - Conventional MOSFET for logic applications
  - Neglect the channel length modulation.

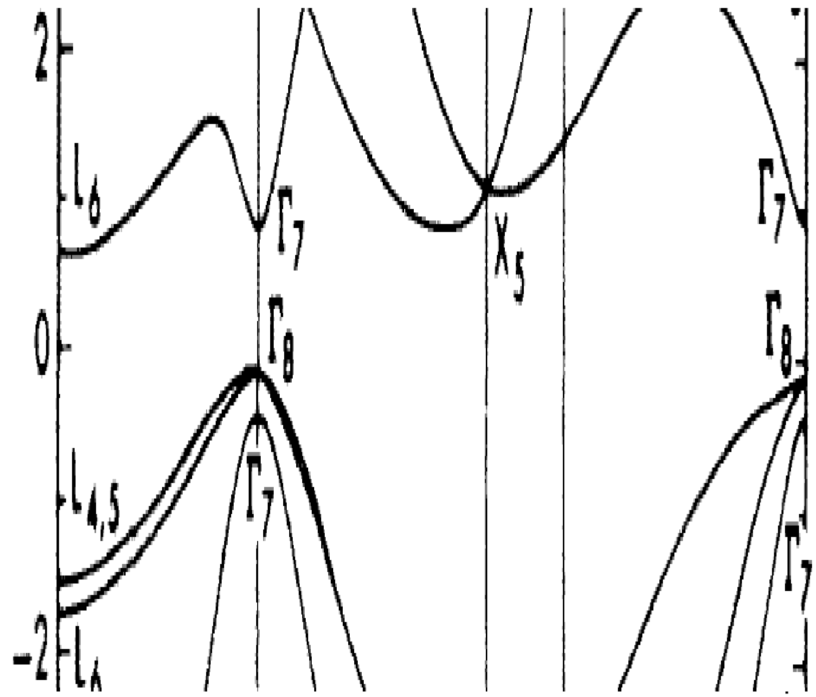
Problem1 (Band structure)

- The band structure of silicon is shown left below.
  - The band structure of a unknown material is shown right below.
  - Energy “0” means the valence band maximum.
  - Estimate the ***band gap*** of the unknown material.

Energy [eV]



Energy [eV]



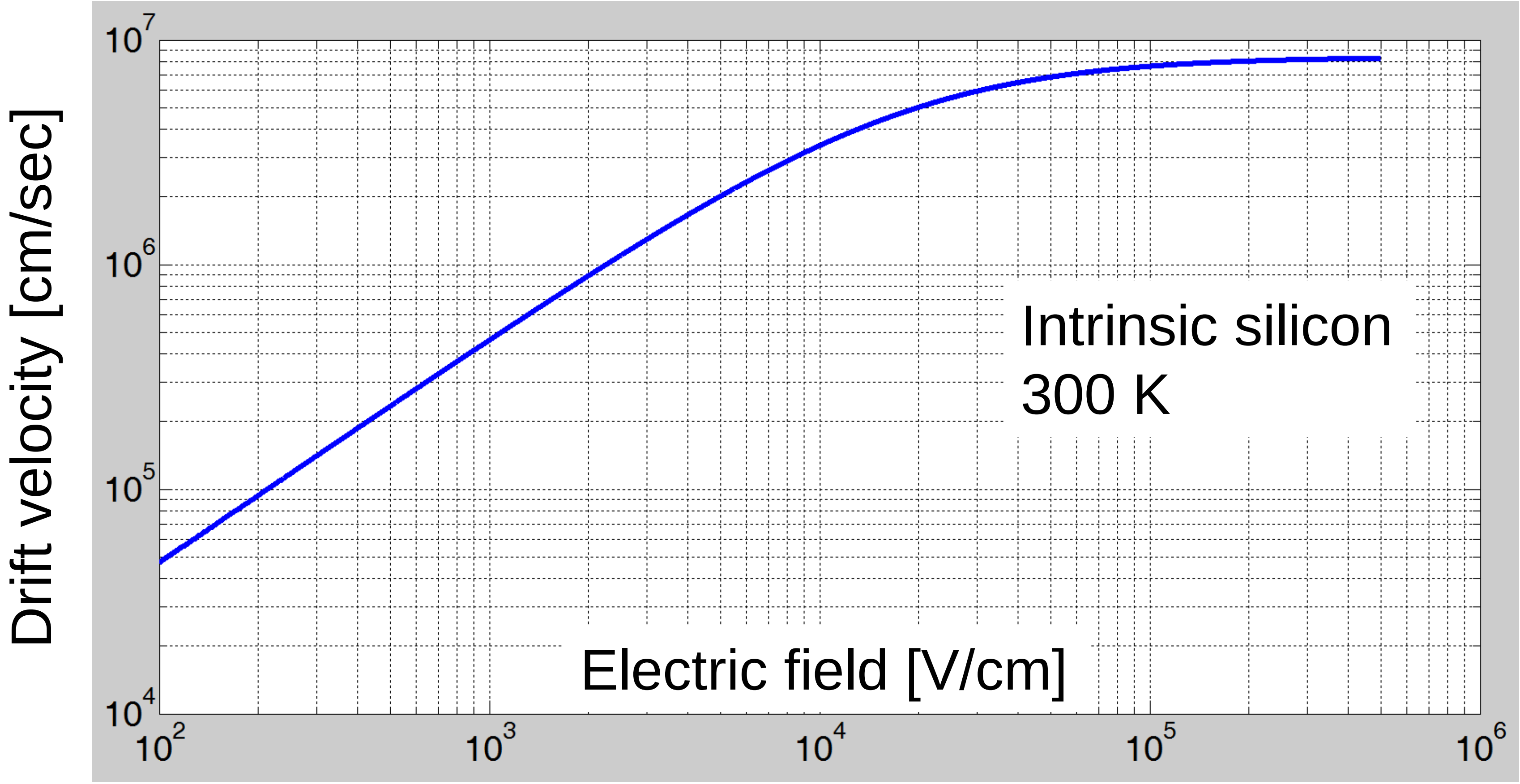
Problem2 (Doping)

- The periodic table is shown below.
  - Arsenic (As) ions are implemented with a dose of $2\text{x}10^{15}$ cm^{-2}.
  - Ions are uniformly distributed with a depth of 0.1 μm.
  - What is the ***electron*** and ***hole densities***, [cm^{-3}], at that region?
  - (You may use the intrinsic carrier density of 10^{10} cm^{-3}, if you want.)

hydrogen 1 H 1.0079																	helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122											boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305											aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29

Problem3 (Mobility)

- Drift velocity is shown below. (Log scale)
  - Estimate the ***low-field mobility*** and ***saturation velocity***.
  - Is the graph for ***electrons or holes***?



Problem4 (Drift and diffusion)

- Consider an one-dimensional structure.
  - The electron current density, J_n, is given by a sum of the drift and diffusion contributions:
  $$J_n = -q\mu_n n \frac{d\phi}{dx} + qD_n \frac{dn}{dx}$$
  - At equilibrium, we have zero current density:
  $$J_n = 0$$
  - Moreover, at equilibrium, the Einstein relation holds:
  $$D_n = \frac{k_B T}{q} \mu_n$$
  - In this case, find out the ***relation between n and ϕ***.

Problem5 (pn junction)

- We studied the built-in potential of a pn junction, V_0.
  - It is given by

$$V_0 = \frac{k_B T}{q} \ln \frac{N_A N_D}{n_i^2}$$

  - ***Derive the above relation***.

Problem6 (pn junction)

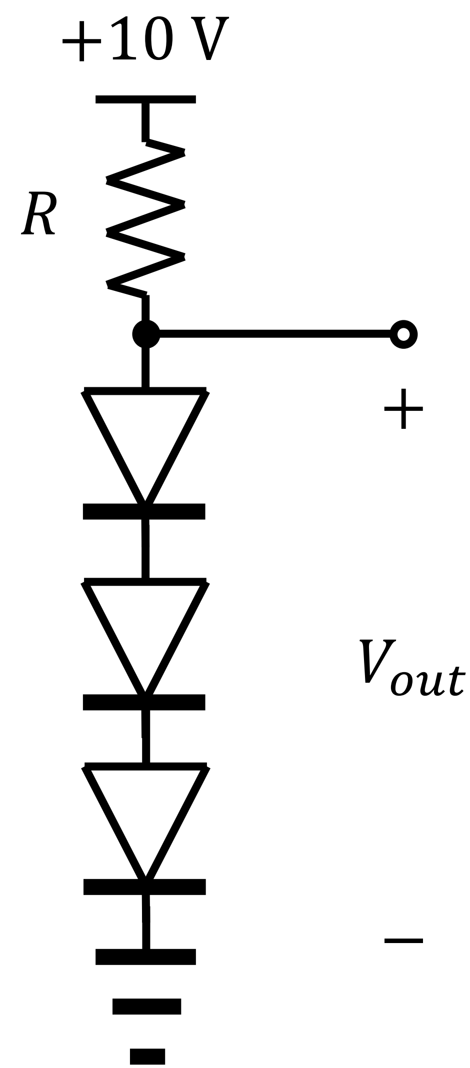
- Consider a pn junction at reverse bias, V_R.
  - The depletion width (in the n-type region) is given by

$$x_n = \sqrt{\frac{2\epsilon_s}{qN_D}\frac{N_A}{N_A + N_D}(V_0 + V_R)}$$

  - Note that V_R is the reverse bias.
  - Then, derive the expression for the ***junction capacitance***.

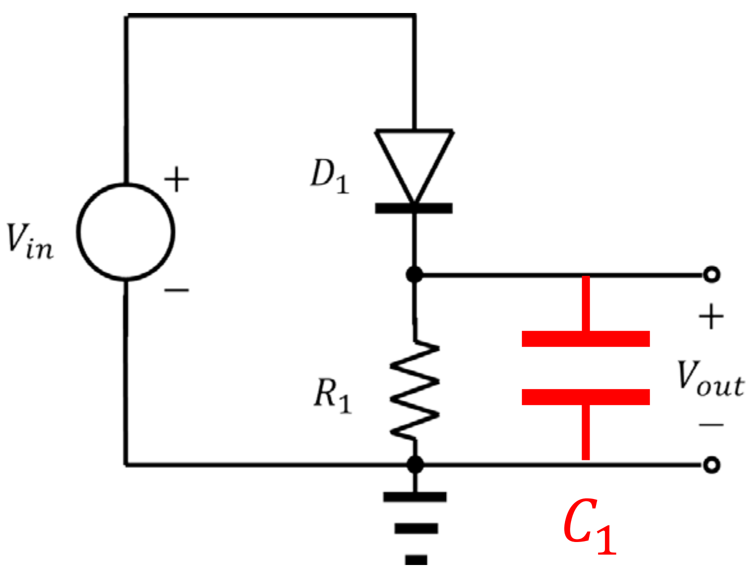
Problem7 (Diode model)

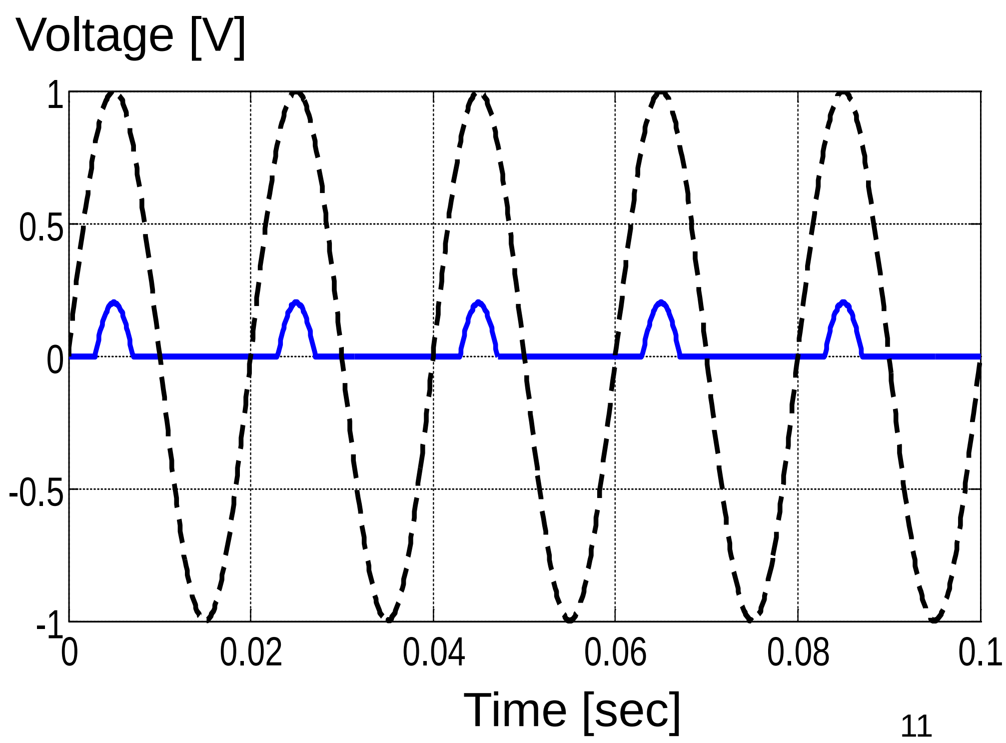
- Use the exponential model.
  - Each diode conducts $1\ \mathrm{mA}$ at $0.7\ \mathrm{V}$.
  - You may use $\exp\left(\frac{0.1\ \mathrm{V}}{V_T}\right) \approx 50$.
  - The output voltage must be $2.4\ \mathrm{V}$.
  - What is the ***value of R***?



Problem8 (Rectifier)

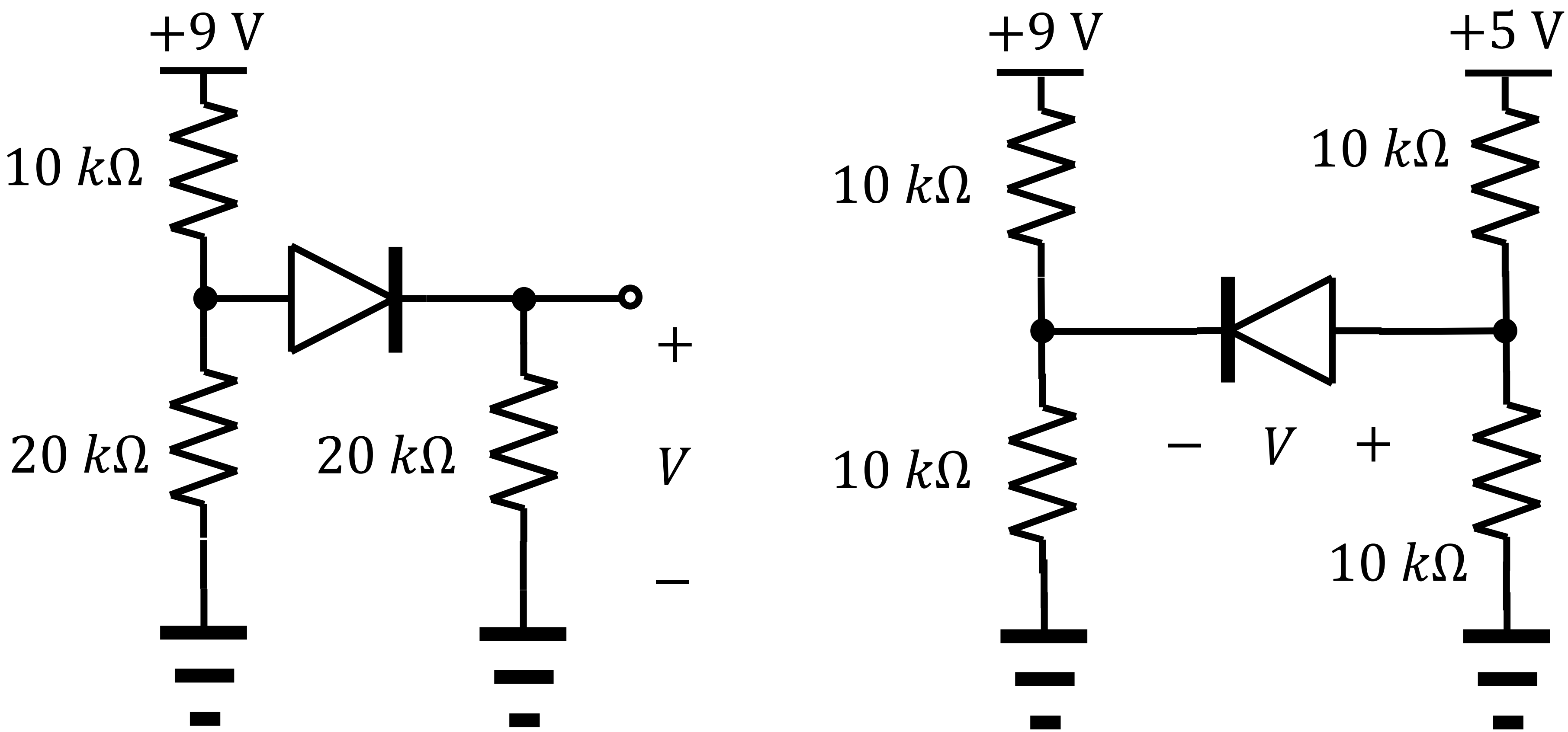
- A half-wave rectifier is shown left below.
  - The expected voltage waveform is shown right below.
  - Now a capacitor, C_1, is connected to the output port.
  - For small and large C_1, draw the ***expected voltage waveforms***.





Problem9 (Diode circuits)

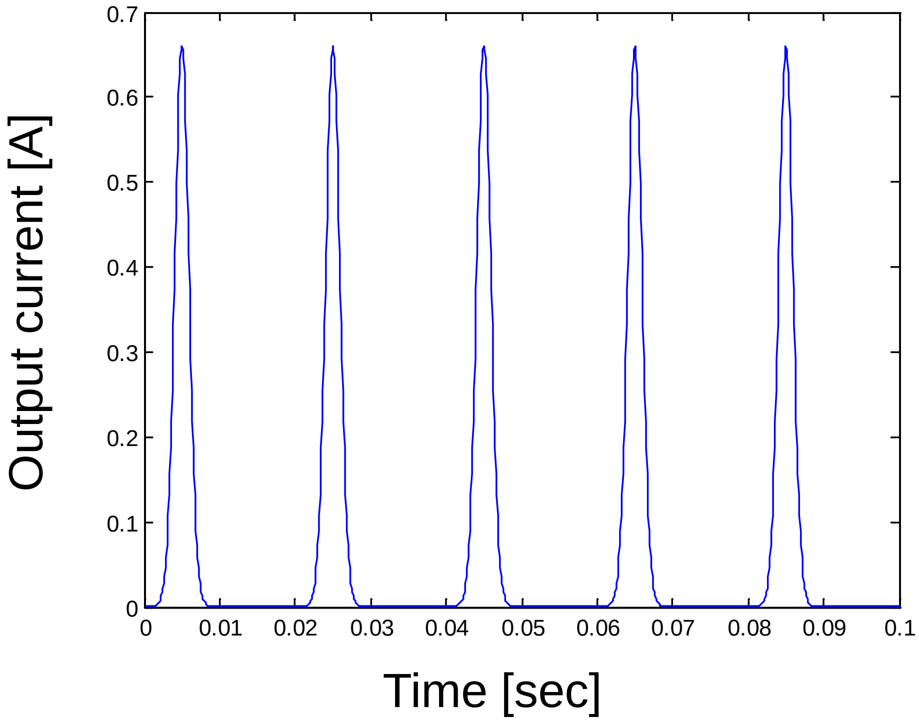
- Two diode circuits are shown below. (Diodes are ideal.)
  - Calculate the ***<u>voltage, V</u>*** for both circuits.



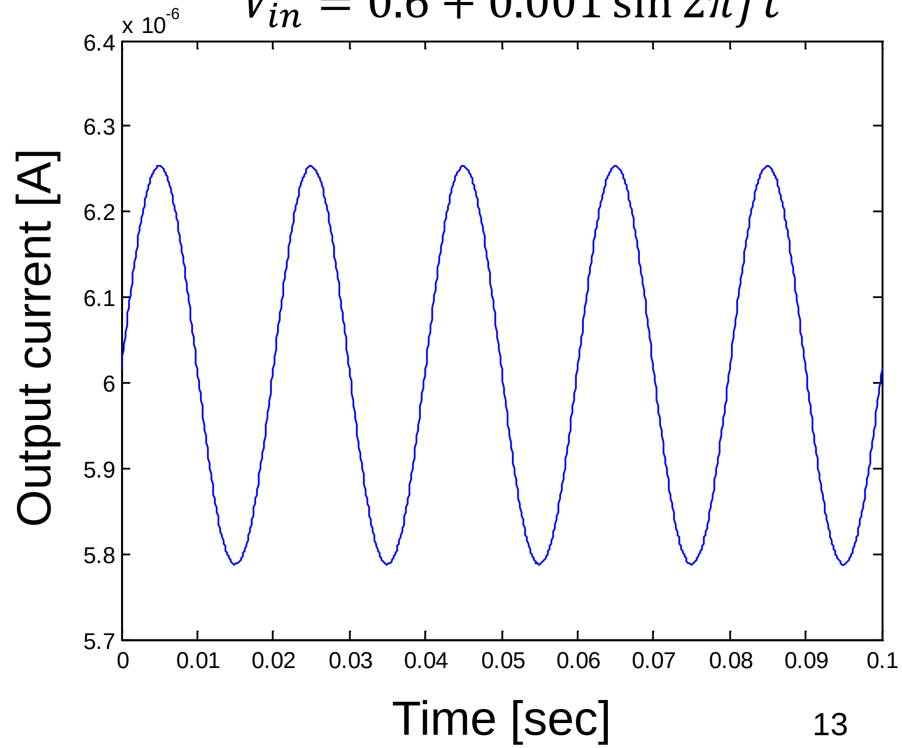
Problem10 (Small-signal)

- A nonlinear system, $I_{out} = I_s \exp \frac{V_{in}}{V_T}$, is considered.
  - Two cases (0.3 V swing and 1 mV swing) are shown below.
  - Explain their ***difference in the frequency domain***.

$$V_{in} = 0.6 + 0.3 \sin 2\pi f t$$

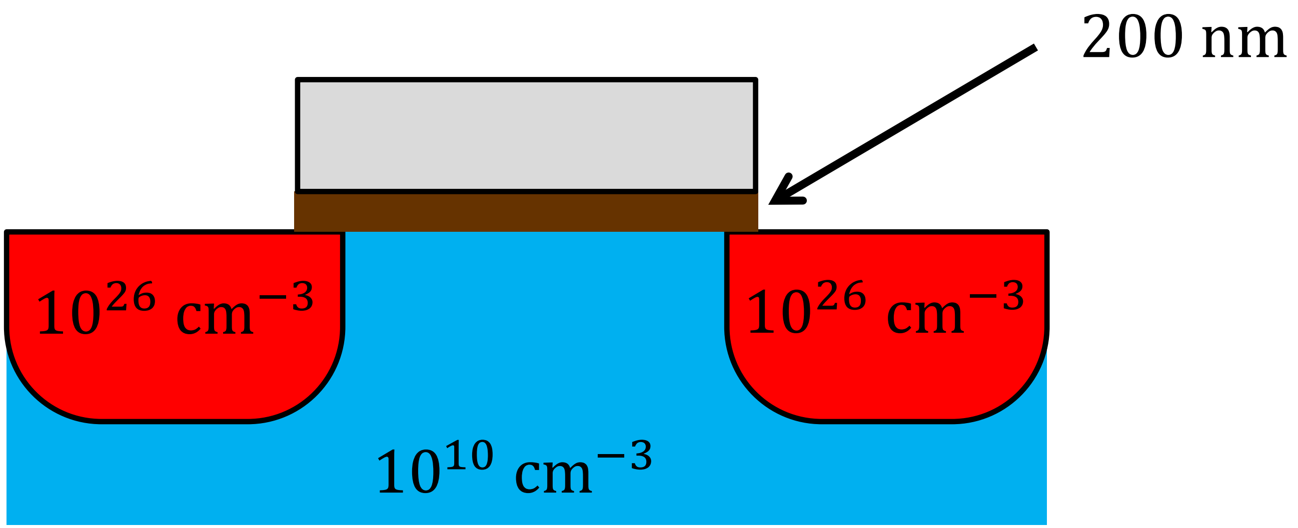


$$V_{in} = 0.6 + 0.001 \sin 2\pi f t$$



Problem11 (MOSFET structure)

- A schematic diagram of an NMOSFET is shown.
  - (Consider a typical one for logic applications.)
  - However, all three parameters – ***oxide thickness***, ***source/drain doping density***, and ***substrate doping density*** – are wrong.
  - Specify reasonable values.



Problem12 (Inversion)

- Consider a MOS structure.
  - The acceptor density of the p-type substrate is N_A.
  - The electric field in the oxide is E_{ox}.
  - (Neglect the electrons in this problem.)
  - Then, what is the ***potential difference between the oxide/semiconductor interface and the substrate***?

Problem13 (Inversion charge density)

- The inversion charge density (per unit area) is given by

$$Q = C_{ox}(V_{GS} - V_{TH})$$

  - Here, C_{ox} is the oxide capacitance ([F/cm^2]) and V_{TH} is the threshold voltage.
  - Consider a device whose dielectric thickness is 2 nm.
  - Assume that the dielectric permittivity is 3.2 x 10^{-13} F/cm.
  - The threshold voltage, V_{TH}, is 0.4 V.
  - Elementary charge is 1.6×10^{-19} C.

  - When the electron sheet density is 10^{12} cm^{-2}, what is the ***gate voltage, V_{GS}***?

Problem14 (Triode region)

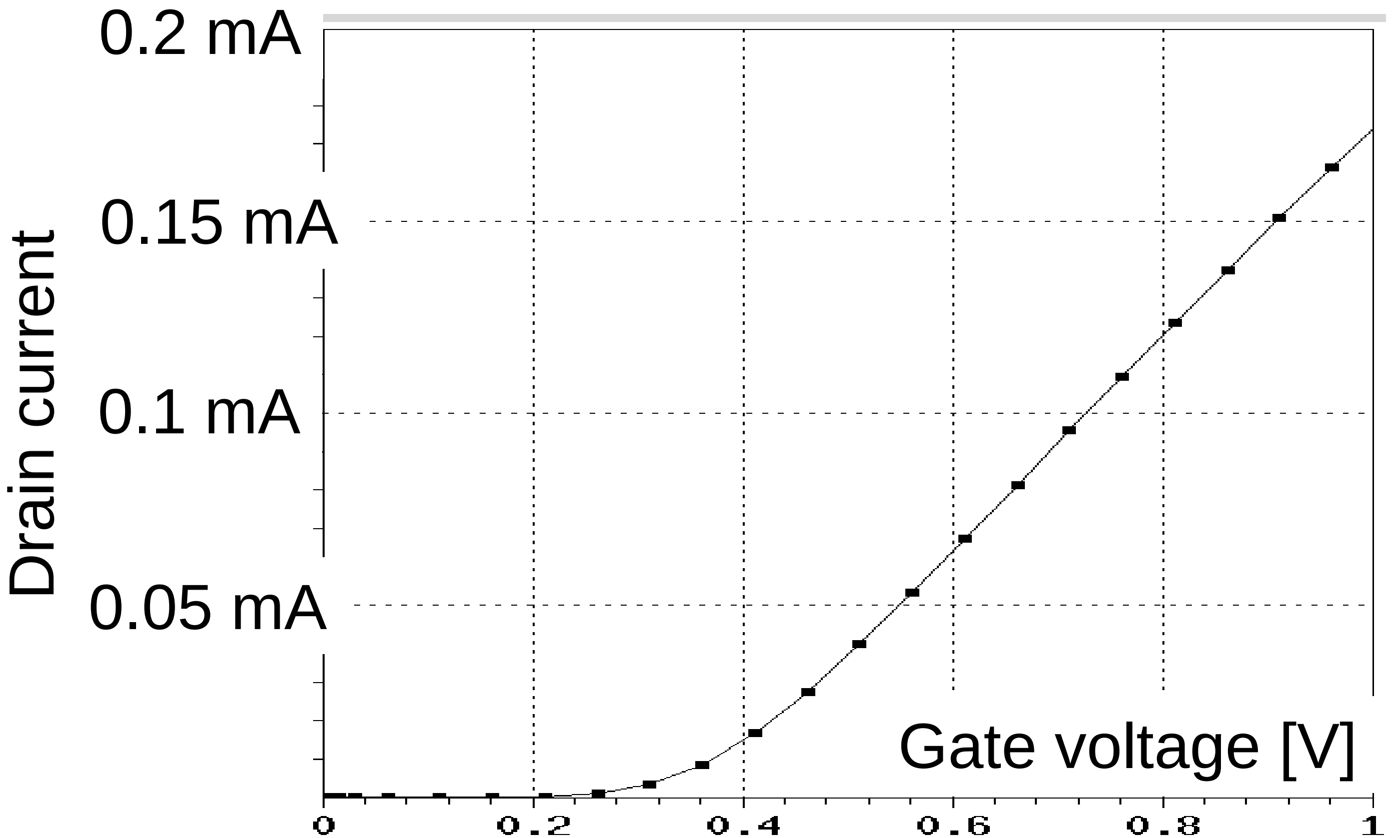
- The drain current at the triode region is given by

$$I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_G - V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2\right]$$

  - ***Derive the above equation explicitly***.

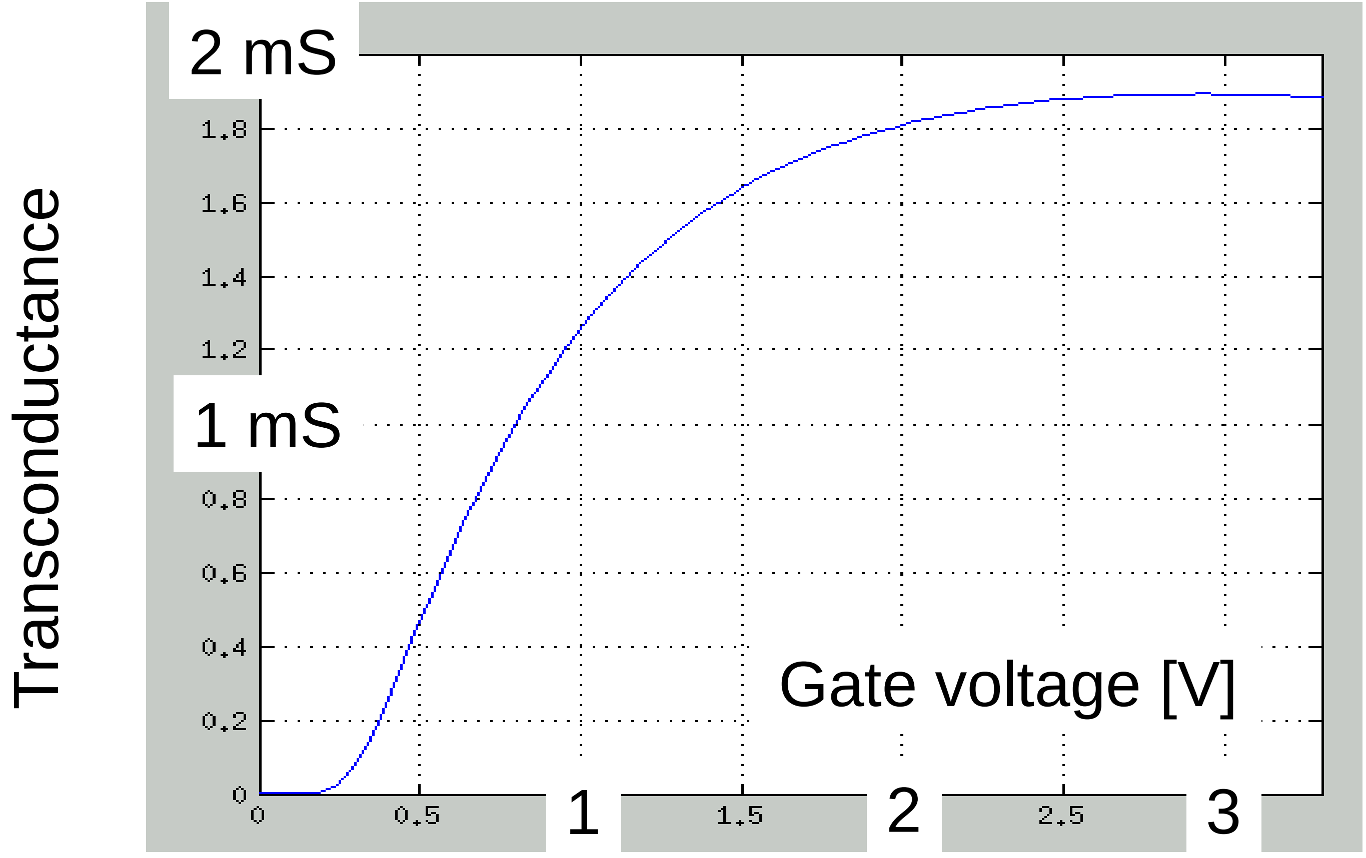
Problem15 (Threshold)

- Simulated Id-Vg curve is shown below.
  - Drain voltage is 0.1 V.
  - Estimate the ***threshold voltage and $\mu_n C_{ox}\frac{W}{L}$***.



Problem16 (Transconductance)

- Transconductance of a long-channel MOSFET is shown.
  - It is operated in the saturation region.
  - What is the ideal behavior? Why does g_m behave differently?

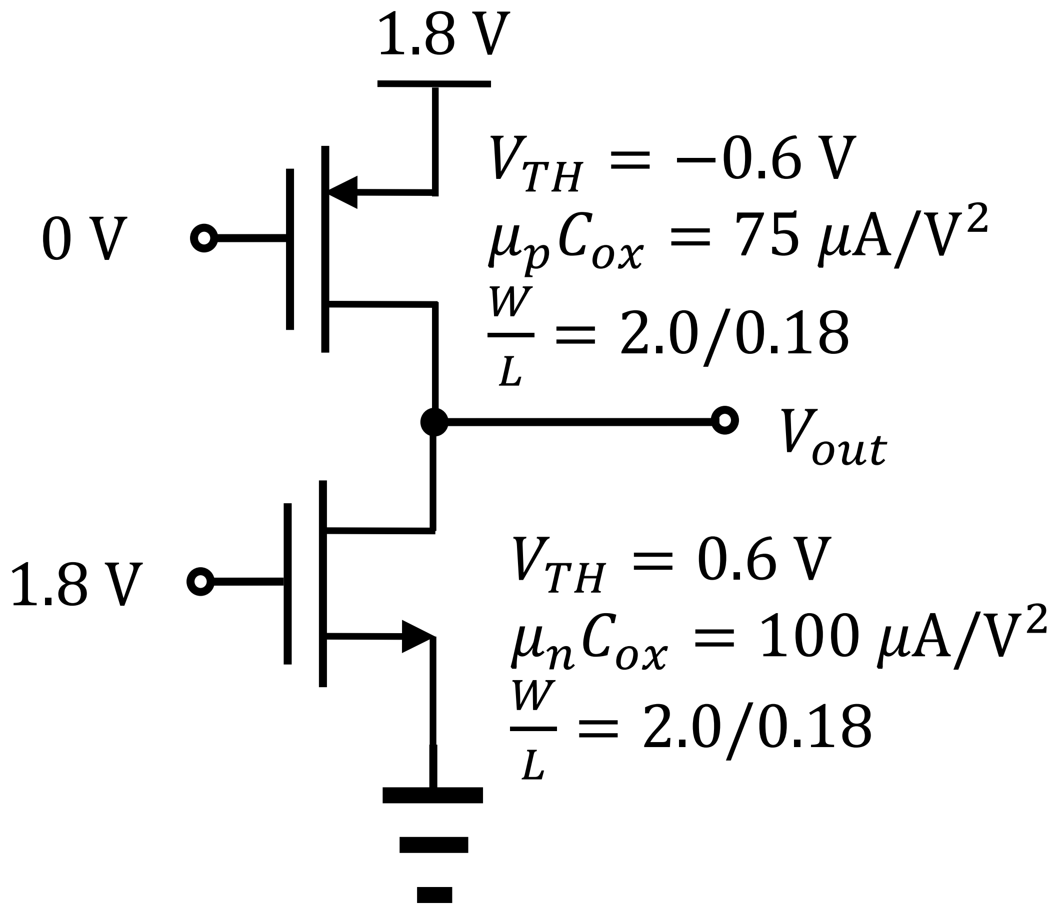


Problem17 (Small-signal model)

- Draw the MOSFET small-signal model.
  - The saturation region is assumed.
  - Include the channel-length modulation.
  - Express the quantities explicitly.

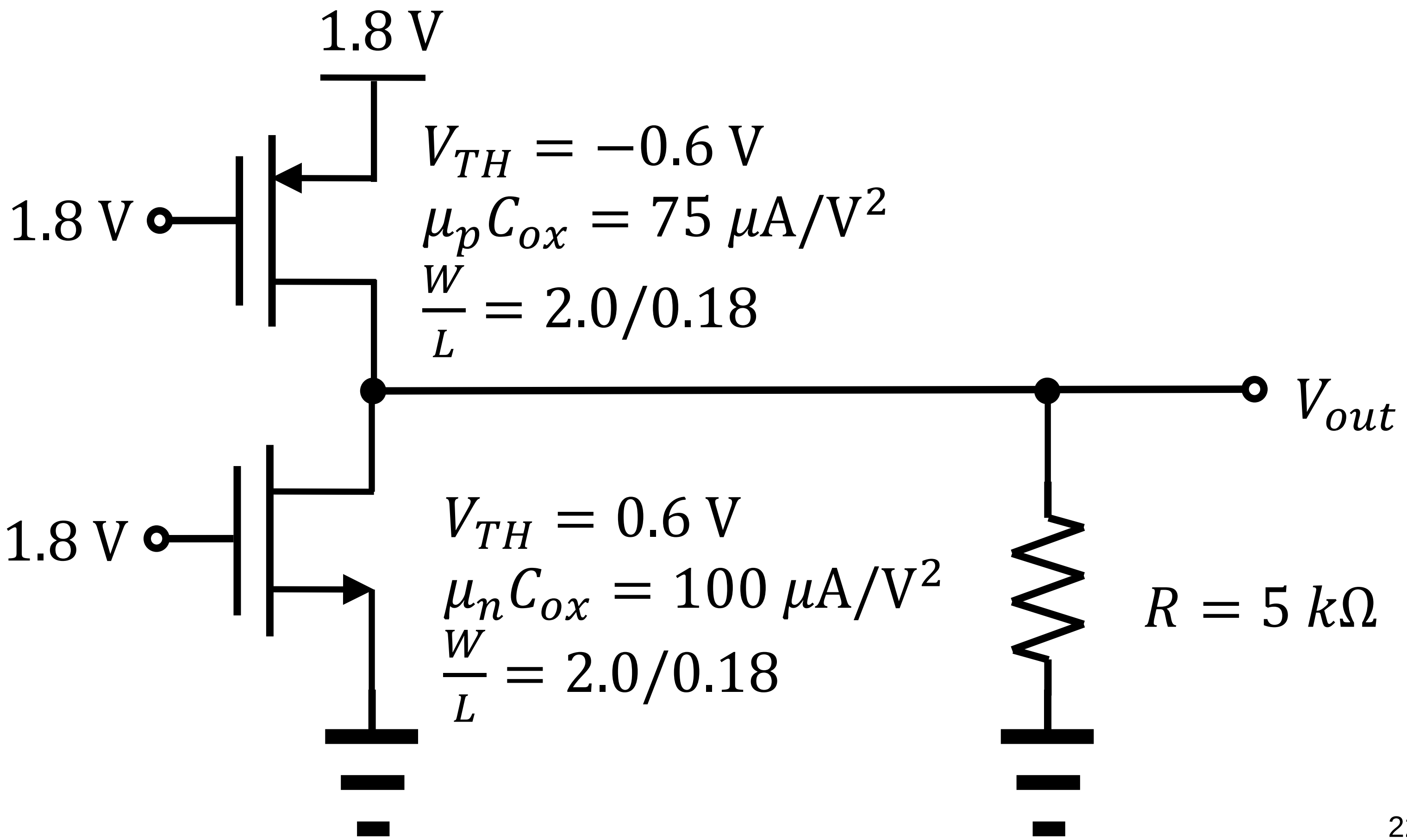
Problem18 (PMOS)

- Calculate the output voltage, V_{out}.
  - Neglect the channel length modulation.



Problem19 (PMOS)

- Calculate the output voltage, V_{out}.
  - Neglect the channel length modulation.



Thank you!

- Submit your answer sheets.
  - The problems will be posted.