NATIONAL EXAMS
MAY 2015

Phys-A5: Semiconductor Devices & Circuits

3 hours duration

NOTES:

1. If doubt exits as to the interpretation of any question, the candidate must submit with the answer paper, a clear statement of any assumption(s) made.

2. Candidates may use one of two calculators, the Casio or Sharp approved models.

3. This is a **CLOSED BOOK EXAM.**
   Useful constants and equations have been annexed to the exam paper.

4. **Any FIVE (5) of the SEVEN (7)** questions constitute a complete exam paper.
   The first five questions as they appear in the answer book will be marked.

5. When answering questions, candidates must clearly indicate units for all parameters used or computed.

MARKING SCHEME

Questions	*Marks*				
1	(a) 5	(b) 5	(c) 10		
2	(a) 3	(b) 4	(c) 8	(d) 5	
3	(a) 4	(b) 6	(c) 4	(d) 6	
4	(a) 4	(b) 2	(c) 5	(d) 4	(e) 5
5	(a) 3	(b) 3	(c) 8	(d) 6	
6	(a) 4	(b) 4	(c) 6	(d) 6	
7	(a) 5	(b) 5	(c) 5	(d) 5	

1. Figure P1a shows the variation of mobility in $cm^2/(V\text{-}s)$ as a function of doping impurity concentration in cm^{-3} at a temperature of T = 300 °K for silicon (Si). Figure P1b shows the saturation of electron drift velocity in *cm/s* as a function of electrical field in *V/cm* for silicon in general.

5 pts (a) Briefly explain why mobility decreases at higher impurity concentration.

5 pts (b) Briefly explain why electron drift velocity saturates in the presence of high electrical fields.

10 pts (c) A bar of silicon of 100 μm^2 in cross-sectional area and length L is doped with 10^{17} donor atoms/cm^3. The bar is used at an ambient temperature of 300 °K and a voltage difference of 10V is applied between the ends of the bar.

i. Estimate the current in the bar when its length L = 0.1 cm.

ii. Estimate the current in the bar when its length L = 0.5 μm.

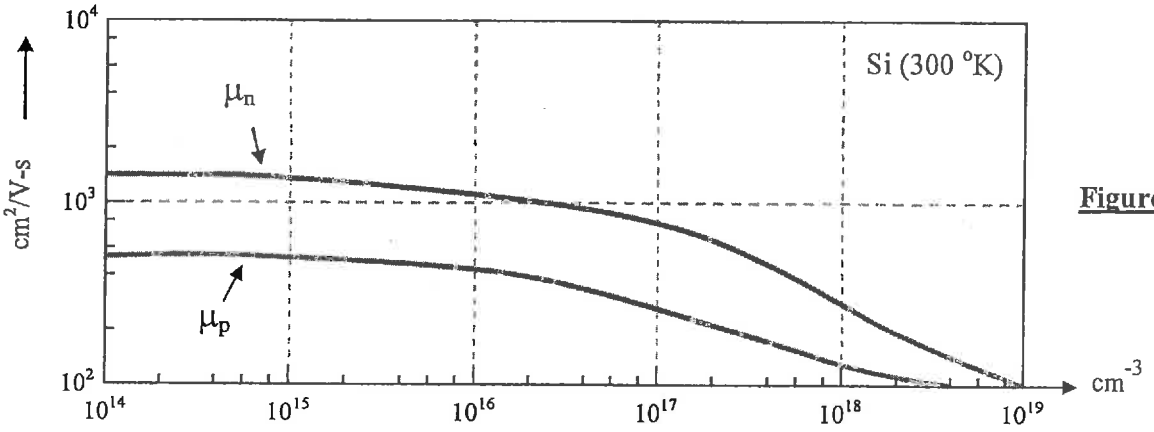


Figure P1a

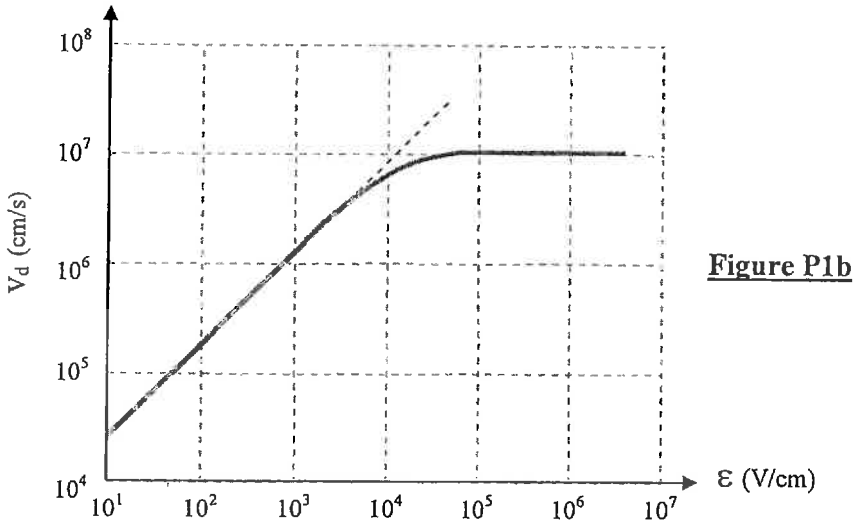


Figure P1b

2. A diode is fabricated by using an abrupt silicon n^+-p junction formed by merging p-type and n-type semiconductors of constant cross section A = 10^{-4} cm^2. The properties of the semiconductors for a temperature of T = 300 °K are shown in Table T2 and the I-V characteristic of the diode is shown in Figure P2. Note that for this semiconductor $\mathbf{n_i = p_i = 2x10^{10}/cm^3}$.

3 pts (a) Calculate the relative Fermi level positions with respect to intrinsic energy levels at 300 °K in the p and n regions.

4 pts (b) Draw an equilibrium band diagram for the junction and determine the contact potential V_o from the diagram.

8 pts (c) What is the value of current I_s shown in Figure P2.

5 pts (d) What is the value of the electrical field in the p-region far from the junction when I = 4 mA?

Table T2 - Properties of junction semiconductors at T = 300 °K ($n_i = p_i = 2x10^{10}/cm^3$)

p type	***n type***
$N_a = 5x10^{15}$ cm^{-3}	$N_d = 10^{18}$ cm^{-3}
$\tau_n = 0.1$ μs	$\tau_p = 10$ μs
$\mu_p = 200$ cm^2/(V-s)	$\mu_n = 1300$ cm^2/(V-s)
$\mu_n = 700$ cm^2/(V-s)	$\mu_p = 450$ cm^2/(V-s)

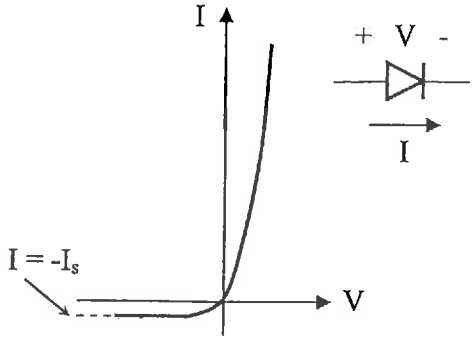


Figure P2

3. An *active second order* filter circuit is shown in Figure P3.

4 pts (a) Briefly explain what the term *active filter* means and list two advantages of using these types of filters.

6 pts (b) Show that the filter transfer function is given by

$$F(s)=\frac{V_3(s)}{V_1(s)}=\frac{-10\,s^2}{s^2+\frac{2}{CR}s+\frac{1}{(CR)^2}}$$

where the *natural frequency* of the filter is $\omega_o = 1/RC$.

4 pts (c) With a brief explanation, determine if the filter is LOW-PASS, HIGH-PASS or PASS-BAND.

6 pts (d) Evaluate the magnitude of *F(s)* <u>in dB</u> and the phase shift of *F(s)* <u>in degrees</u> of this filter when the frequency of the input signal is $\omega = 0.5\omega_o$.

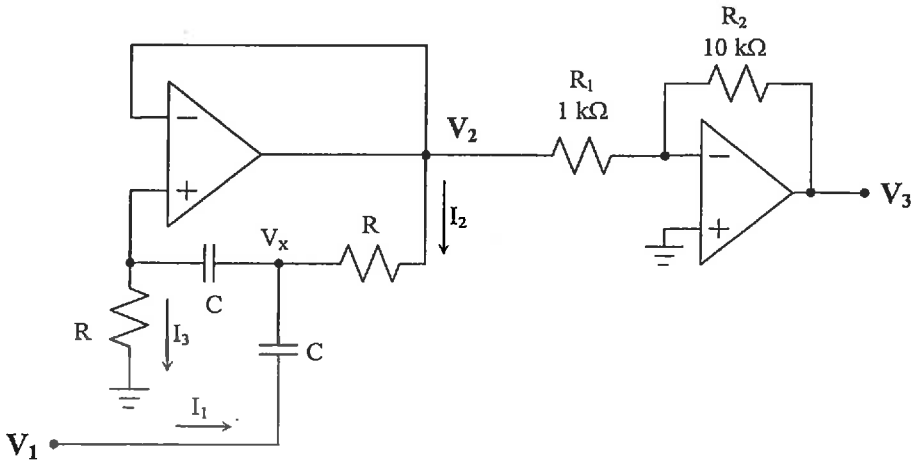


Figure P3

4. A single stage small signal amplifier is shown in Figure P4. The MOSFET device in the circuit needs to be biased to set the DC drain current at $I_D = 1$ mA and $V_{DS} = 10$ V. This requires that $V_{GS} = 1$ V. At that operating point, the small signal parameters of the device are $g_m = 4$ mA/V and $r_o = 500$ kΩ. The low frequency response of this amplifier is given by

$$G(s) = \frac{V_o(s)}{V_i(s)} = A_{vm} \frac{s}{(s+\omega_{p1})} \frac{(s+\omega_z)}{(s+\omega_{p2})} \frac{s}{(s+\omega_{p3})}$$

where A_{vm} is the midband voltage gain, and

$$\omega_z = \frac{1}{R_s C_s} \qquad \omega_{p1} = \frac{1}{(R_{sig} + R_{in}) C_i} \qquad \omega_{p2} = \frac{1}{(R_S \| \frac{1}{g_m}) C_S} \qquad \omega_{p3} = \frac{1}{(R_{out} + R_L) C_o}$$

4 pts (a) Briefly explain the main purpose of using capacitors in the circuit of Figure P4.

2 pts (b) Draw the mid-band small signal equivalent circuit of the amplifier and show that the output resistance $\mathbf{R_{out} = 4.95\ k\Omega}$.

5 pts (c) Select suitable values for resistors R_1 and R_2 to meet both of the following requirements:

$$\mathbf{V_{GS} = 1\ V} \quad \text{and} \quad \mathbf{R_{in} = 420\ k\Omega}$$

4 pts (d) Calculate the mid-band voltage gain $\mathbf{A_{vm} = v_o/v_{sig}}$.

5 pts (e) Select an appropriate value for capacitor $\mathbf{C_o}$ to make pole ω_{p3} the *dominant* factor in the frequency response.

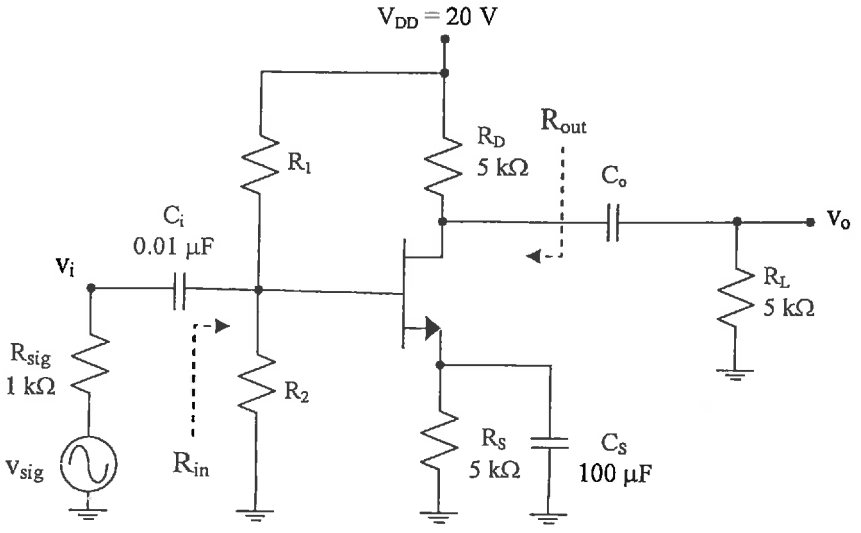


Figure P4

5. Three different inverters are shown in Figures P5a, P5b and P5c, and a typical voltage transfer characteristic (VTC) appears in Figure P5d. Also, a logic circuit composed of identical inverters and its periodic signal **v(t)** are shown Figure P5e.

3 pts (a) Name the logic family of each of the three inverters shown in Figures P5a, P5b and P5c.

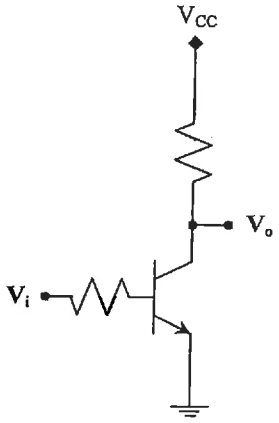
3 pts (b) List one advantage and one disadvantage of each type of inverters.

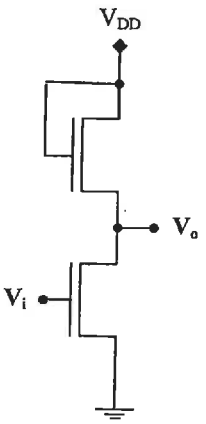
8 pts (c) For an inverter which has the VTC shown in Figure P5d, graphically extract:

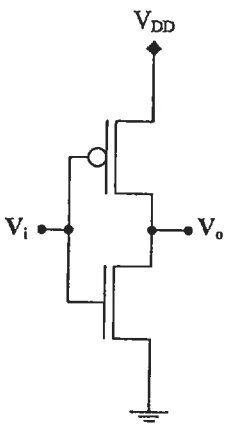
i. the values of its noise margins NM_L and NM_H
ii. the value of its switching voltage
iii. the value of its gain

6 pts (d) For the structure shown in Figure P5e,

i. state the name of the logic circuit
ii. briefly explain why the rise time of signal **v(t)** would differ from its fall time
iii. calculate the average propagation delay of the single inverter used in the logic circuit if T = 20 ns.







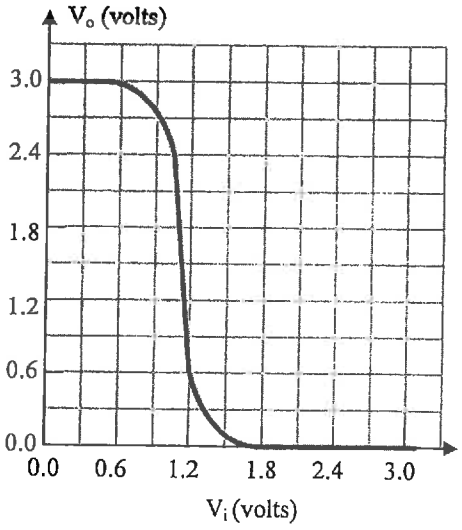


Figure P5a **Figure P5b** **Figure P5c** **Figure P5d**

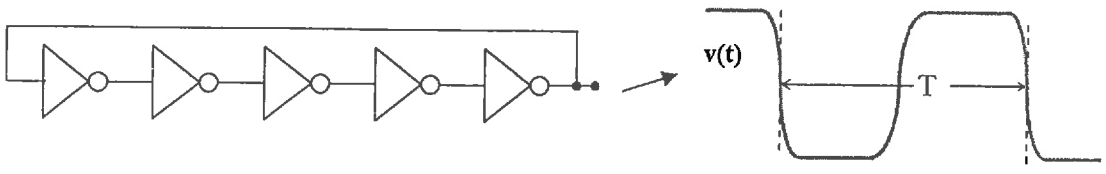


Figure P5e

6. The temperature controller circuit shown in Figure P6 detects the value of the ambient temperature of a room and uses an *n*-bit analog-to-digital converter (ADC) to provide a digital signal to a thermostat. The ambient temperature range is $0 \le T \le 30$ °C. This range of temperature is linearly converted by a transducer to an analog voltage range of $0 \le V_A \le 3$ V.

4 pts (a) State the name of the type of ADC used in the temperature controller circuit and its main disadvantage.

4 pts (b) Briefly explain what limits the speed of conversion of this type of ADC.

6 pts (c) If $V_{ref} = 3.1$V, determine the minimum number of bits *n* required to code the digital signal in order for the temperature controller to have a resolution of at least 0.25 °C.

6 pts (d) For the value of *n* found in (c), what would be the value of the digital (binary) signal sent to the thermostat?

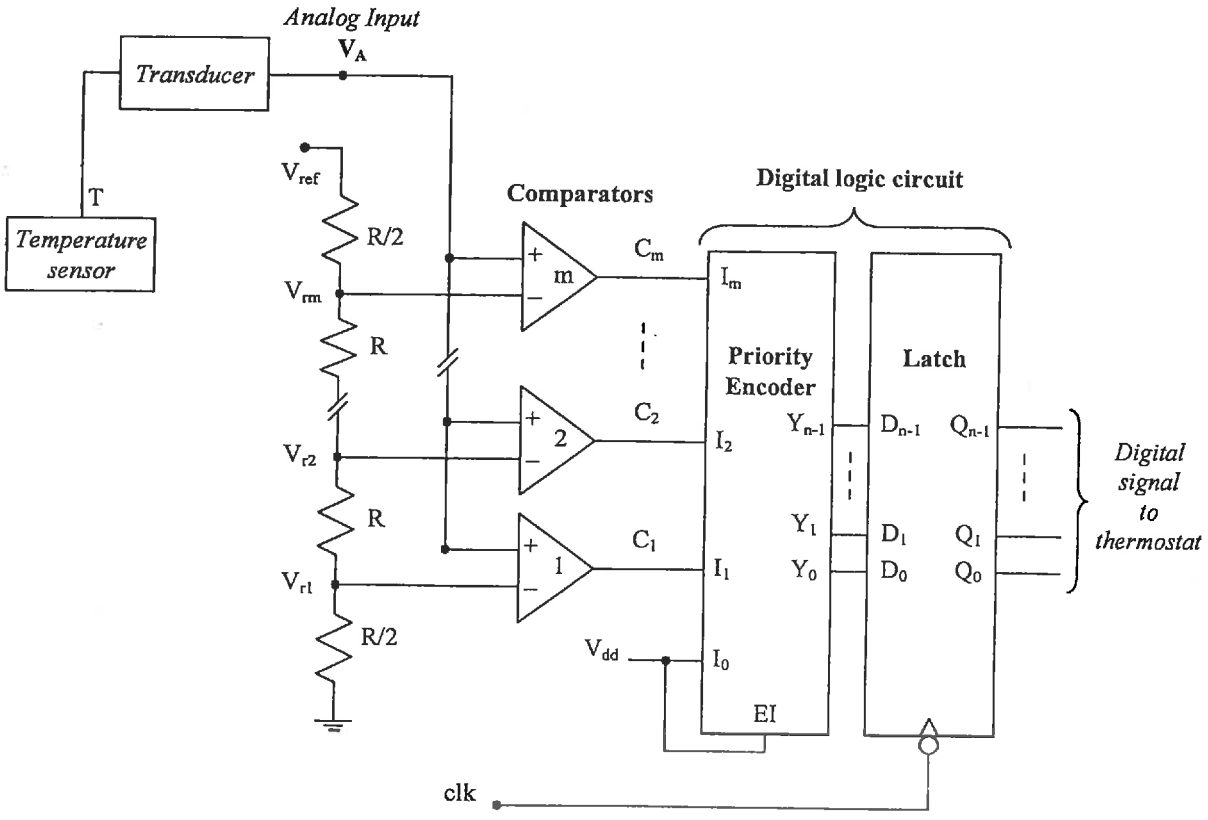


Figure P6

7. An instrumentation equipment requires the generation of square and triangular waveforms with amplitudes varying between +5 V and – 5V, both signals having a frequency equal to 1 kHz. The circuit shown in Figure P7 is used to generate these two signals. A capacitor C = 0.01 μF must be used for the integrator section. The bistable section must be designed for precision by using four diodes having a rating of $V_D = 0.7$ V and a Zener diode of rating V_Z . The current in the Zener diode must be equal to 1 mA and the current flowing in resistors R_1 and R_2 must not exceed 0.2 mA. The OP amps used in the circuit have output saturation levels equal to +13 V and –13 V. Figure P7 also shows the flow of currents when signal V_2 switches to +5 V.

   Assuming that OP amps are ideal (except for their output saturation levels), find values of components and ratings to meet the above specifications.

   Proceed in the following order:

5 pts (a) Find the required voltage rating V_Z for the Zener diode.

5 pts (b) Determine the required values of resistors R_1 et R_2 for the bistable section.

5 pts (c) Determine the required value of resistor R for the integrator section.

5 pts (d) Determine the required value of resistor R_d for the bistable section.

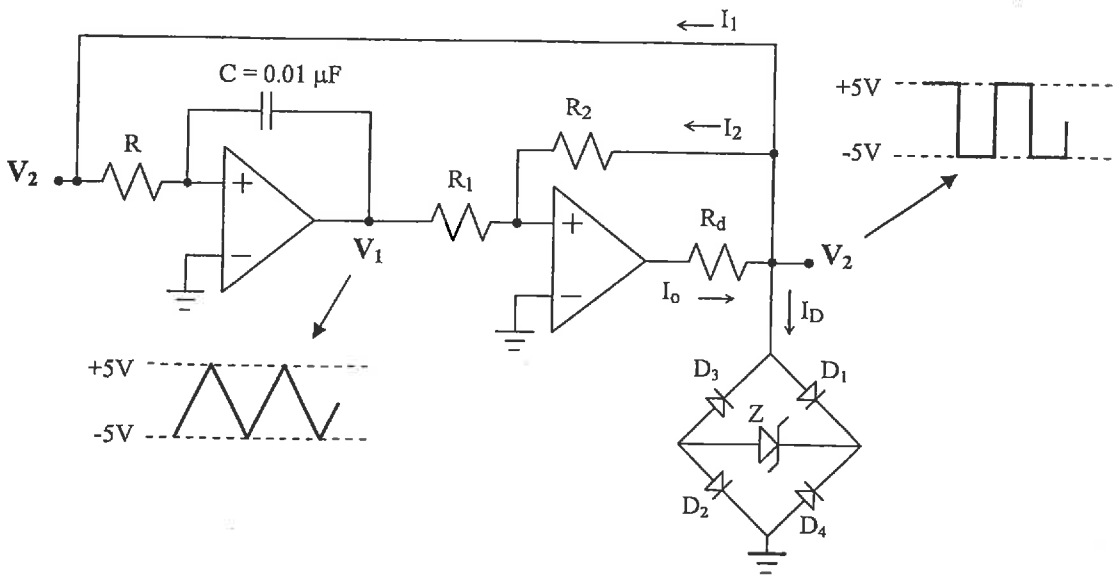


Figure P7

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ANNEX: USEFUL CONSTANTS, EQUATIONS and MODELS

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(1) $1\ \mathring{A} = 10^{-10}$ m $= 10^{-8}$ cm $= 10^{-4}$ μm

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

(3) $k = 1.38 \times 10^{-23}$ J/°K $= 8.62 \times 10^{-5}$ eV/°K [At T = 300°K, kT = 0.026 eV, $V_T = kT/q \approx 26$ mV]

(4) Avogadro's Number $A_N = 6.02 \times 10^{23}$ /mole

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(5) For silicon (Si) at T = 300 °K: $n_i = 1.5 \times 10^{10}/cm^3$

(6) $\varepsilon_{Si} = 1.04 \times 10^{-12}$ F/cm

(7) $\varepsilon_{SiO2} = 0.345 \times 10^{-12}$ F/cm [farad: 1 F = 1 C/V] [siemens: 1 mS = 1 mA/V = 1 mmho]

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(8) $$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

(9) $$n_o + N_a = p_o + N_d$$

(10) $$n_o\, p_o = n_i^{\,2}$$

(11) $$n_o = N_c e^{(E_F - E_c)/kT} = n_i e^{(E_F - E_i)/kT}$$

(12) $$p_o = N_v e^{(E_v - E_F)/kT} = n_i e^{(E_i - E_F)/kT}$$

(13) $$n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT}$$

(14) $$V_o = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$$

(15) $$W = \sqrt{\frac{2\varepsilon_{Si} V_o}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}$$

(16) $$x_{po} = \frac{W N_d}{N_a + N_d} \qquad x_{no} = \frac{W N_a}{N_a + N_d}$$

(17) $$E(x) = \int \frac{\rho(x)}{\varepsilon} dx \qquad \phi(x) = -\int E(x) dx$$

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(18) $$\mu = \frac{v_{drift}}{\mathcal{E}}$$

(19) $$\sigma = q(n_o \mu_n + p_o \mu_p)$$

(20) $\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = \frac{kT}{q}$ $\qquad L_n = \sqrt{D_n \tau_n}$ $\qquad L_p = \sqrt{D_p \tau_p}$

(21) $n_n p_n = n_i^2 = n_p p_p$

(22) $I = I_o(e^{\frac{qV}{kT}} - 1) = qA\left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p\right)(e^{\frac{qV}{kT}} - 1)$

(23) $J = \frac{I}{A} = \sigma \mathcal{E}$

(24) $R = \frac{L}{\sigma A}$

(25) $R_H = \frac{1}{q(p_o - n_o)}$

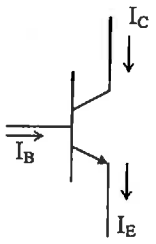
BJT relationships and model

(26) $I_C = \beta I_B$ where $\beta = I_C/I_B$

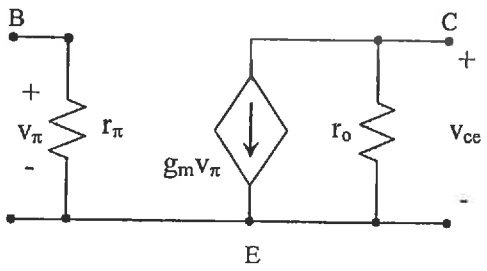
(27) $I_E = I_B + I_C$

(28) $g_m = I_C/V_T$

(29) $r_\pi = V_T/I_B$



Small signal BJT model



MOS device in a p substrate

(30) $\phi_F = \frac{kT}{q} \ln \frac{N_a}{n_i}$

(31) $W_m = 2\sqrt{\frac{\varepsilon_{Si}\phi_F}{qN_a}}$

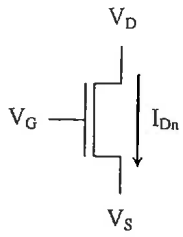
(32) $Q_d = -qN_aW_m$

(33) $C_i = \frac{\varepsilon_{SiO_2}}{d}$

(34) $V_T = \Phi_{ms} + 2\phi_F - \frac{1}{C_i}(Q_i + Q_d)$

MOSFET symbols, relationships and model

(36) $g_m = \dfrac{\partial I_D}{\partial V_{GS}}$

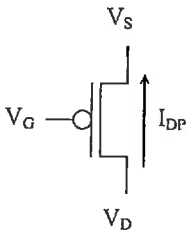


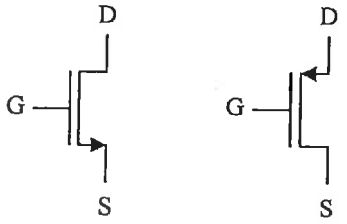
(37) $I_{Dn} = (k_n/2)\,(V_{GSn} - V_{tn})^2$ when $V_{DSn} > V_{GSn} - V_{tn}$

(38) $I_{Dn} = (k_n/2)\,[2(V_{GSn} - V_{tn})(V_{DSn}) - (V_{DSn})^2]$ when $V_{DSn} < V_{GSn} - V_{tn}$

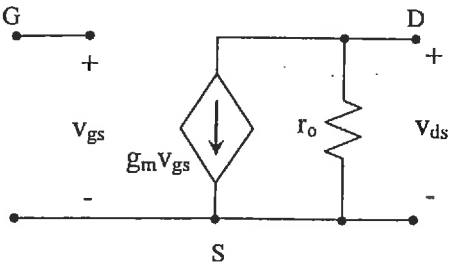
(39) $I_{Dp} = -(k_p/2)\,(V_{GSp} - V_{tp})^2$ when $V_{DSp} < V_{GSp} - V_{tp}$

(40) $I_{Dp} = -(k_p/2)\,[2(V_{GSp} - V_{tp})(V_{DSp}) - (V_{DSp})^2]$ when $V_{DSp} > V_{GSp} - V_{tp}$





Small signal MOSFET model



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(41) For complex number $R = Aj + B$, $|R| = (A^2+B^2)^{1/2}$ and $\phi(R) = tan^{-1}(A/B)$

(42) $V_o(t) = -\dfrac{1}{RC}\int_0^T V_i(t)dt$ $\qquad \dfrac{V_o(s)}{V_i(s)} = \dfrac{-1}{sRC}$ [integrator circuit]

(43) $V_{DC} \equiv V_{average} = \dfrac{1}{T}\int_0^T V(t)dt$ $= V_p/\pi$ for a half-wave sinewave and $2V_p/\pi$ for full-wave sinewave

(44) $V_{rms} = \sqrt{\dfrac{1}{T}\int_0^T [V(t)]^2 dt}$ $= \dfrac{V_p}{2}$ for a half-wave sinewave and $\dfrac{V_p}{\sqrt{2}}$ for full-wave sinewave