NATIONAL EXAMS
MAY 2017

98-Phys-A5: Semiconductor Devices &

Circuits Duration: 3 hours

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) 3	(b) 3	(c) 5	(d) 5	(e) 4
2	(a) 3	(b) 6	(c) 4	(d) 7	
3	(a) 4	(b) 4	(c) 6	(d) 6	
4	(a) 3	(b) 3	(c) 5	(d) 4	(e) 5
5	(a) 8	(b) 5	(c) 2	(d) 5	
6	(a) 3	(b) 6	(c) 6	(d) 5	
7	(a) 8	(b) 8	(c) 4		

1. Figure P1 shows a silicon bar of length L and cross-sectional area of 100 μm^2 connected in series with a 10V battery. The bar is doped with 10^{17} donor atoms/cm^3. At 300 °K, this corresponds to an electron mobility of 700 cm^2/V-s and electron drift velocity saturation of 10^7 cm/s for any electrical field E exceeding $E_{sat} = 10^4$ V/cm.

3 pts (a) Briefly explain why electron mobility would decrease if the donor concentration was augmented.

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

5 pts (c) Estimate the current I in the bar when its length L = 0.1 cm.

5 pts (d) Estimate the current I in the bar when its length L = 0.5 μm.

4 pts (e) Evaluate the Hall coefficient of the semiconductor bar.

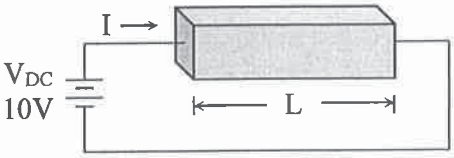


Figure P1

2. A diode is fabricated by using an abrupt silicon P-N$^+$ junction formed by merging P-type and N-type semiconductors of constant cross section $A = 10^{-4}$ cm^2. The device is used in an ambient temperature of $T = 300$ °K. The equilibrium band diagram and current-voltage characteristic of the diode are shown at the right-hand side of Figure P2. The basic properties of the P-type and N-type semiconductors for a temperature of $T = 300$ °K are shown in the table below.

P type	**N type**
$p_i = 2\times10^{10}$ cm^{-3}	$n_i = 2\times10^{10}$ cm^{-3}
$\tau_n = 0.1\ \mu$s	$\tau_p = 10\ \mu$s
$\mu_p = 200$ 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)

3 pts (a) Based on the band diagram, what is the value of the *contact potential* of the P-N junction?

6 pts (b) Evaluate the concentration of *majority* carriers, p_p and n_n, on each side of the P-N junction.

4 pts (c) Evaluate the concentration of *minority* carriers, n_p and p_n, on each side of the P-N junction.

7 pts (d) If the impurity concentrations are adjusted such that $n_p = 1.35\times10^5$ cm^{-3} and $p_n = 324$ cm^{-3} what is the value of the *reverse saturation current* of the P-N junction?

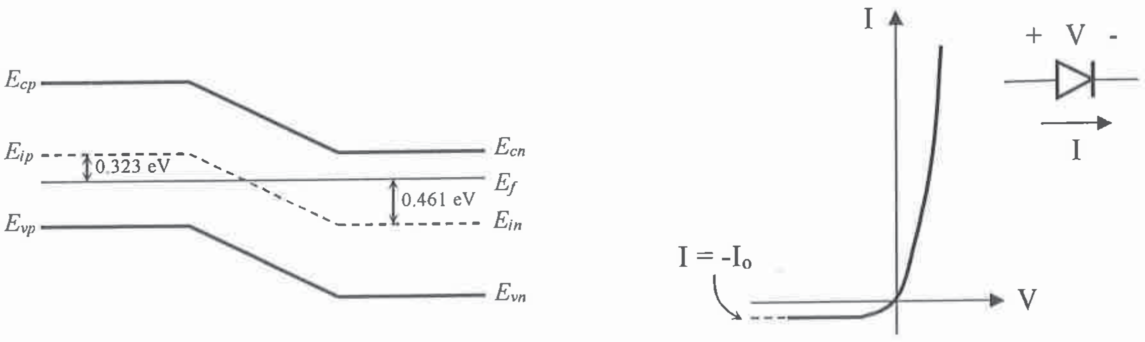


Figure P2

3. A second order high-pass *active* filter circuit is shown in Figure P3.

4 pts (a) List two advantages of *active* filters?

4 pts (b) If the OP amps are considered ideal, what are the values of input impedance $\mathbf{R_{in}}$ and output impedance $\mathbf{R_{out}}$?

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

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

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

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

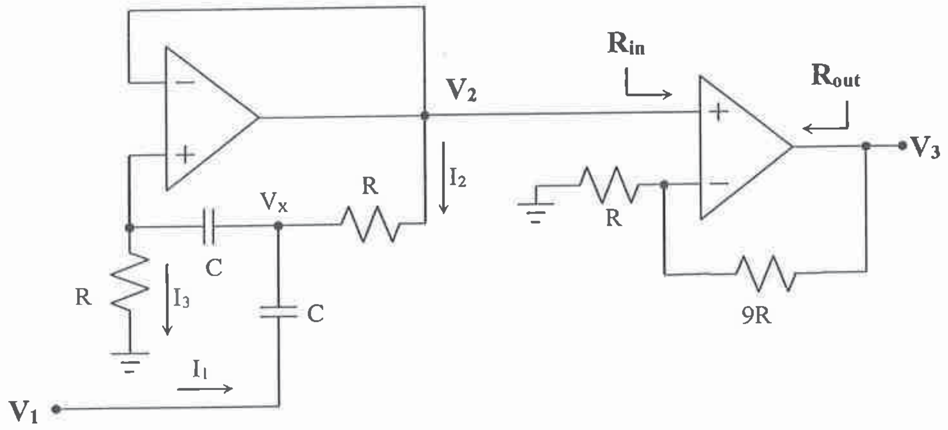


Figure P3

4. A single stage small signal amplifier is shown in Figure P4. The MOSFET device in the circuit needs to be biased such that the DC drain current $I_D = 1$ mA and drain-source voltage $V_{DS} = 10$ V. To obtain these values, the gate-source voltage must be set to $V_{GS} = 1$ 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

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

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

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

3 pts (a) Briefly explain the main purpose of using capacitor C_s in the circuit of Figure P4.

3 pts (b) Draw the midband small signal equivalent circuit of the amplifier and show that the output resistance $\mathbf{R_{out}}$ of the amplifier is equal to **4.95 kΩ.**

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

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

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

5 pts (e) If the high frequency response of this amplifier is given by

$$G_H(s) = A_{vm} \frac{1}{(1+s/\omega_H)} \quad \text{where} \quad \omega_H = 90 \text{ krad/s},$$

evaluate the bandwidth of this amplifier.

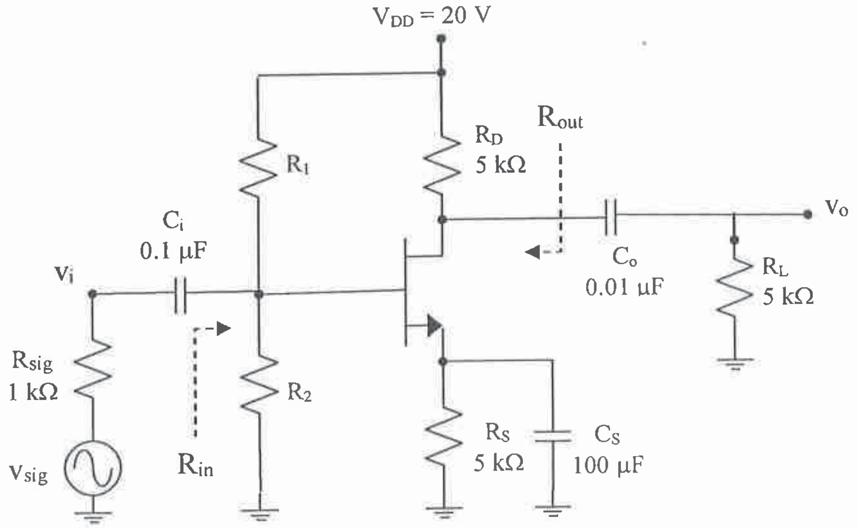


Figure P4

5. Figure P5a shows a CMOS inverter circuit and its related voltage transfer characteristic (VTC). Figure P5b shows a ring oscillator built with five identical versions of the same CMOS inverter.

8 pts (a) From the VTC shown in Figure P5a, graphically extract approximate values for:

i. the LOW noise margin NM_L;
ii. the HIGH noise margin NM_H;
iii. the switching voltage V_x; and
iv. the small signal gain.

Briefly explain how each of the four parameters was graphically extracted.

5 pts (b) Calculate the exact value of the switching voltage if fabrication parametric measurements show that $k_n = 3k_p$, $V_{tn} = 0.4$ V and $V_{tp} = -0.5$ V.

2 pts (c) Briefly explain how the inverter circuit could be modified to make the switching voltage equal to 1.5V (half the supply voltage V_{DD}).

5 pts (d) If the inverter is designed with timing parameters t_{phl} and t_{plh} that are equal to 1.8 ns and 2.2 ns respectively, calculate the frequency of output signal **v(t)** coming out of node **N** of the ring oscillator circuit shown in Figure P5b.

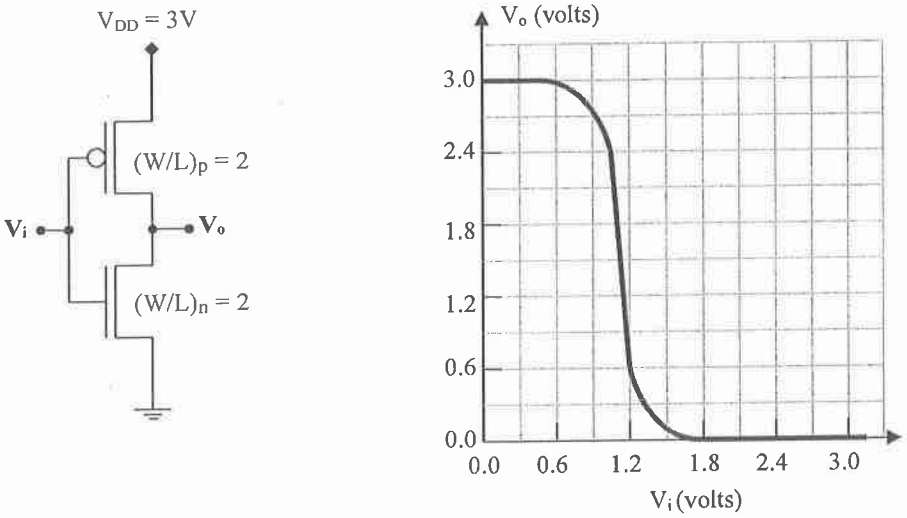


Figure P5a

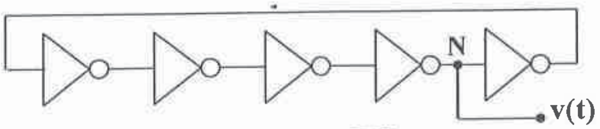


Figure P5b

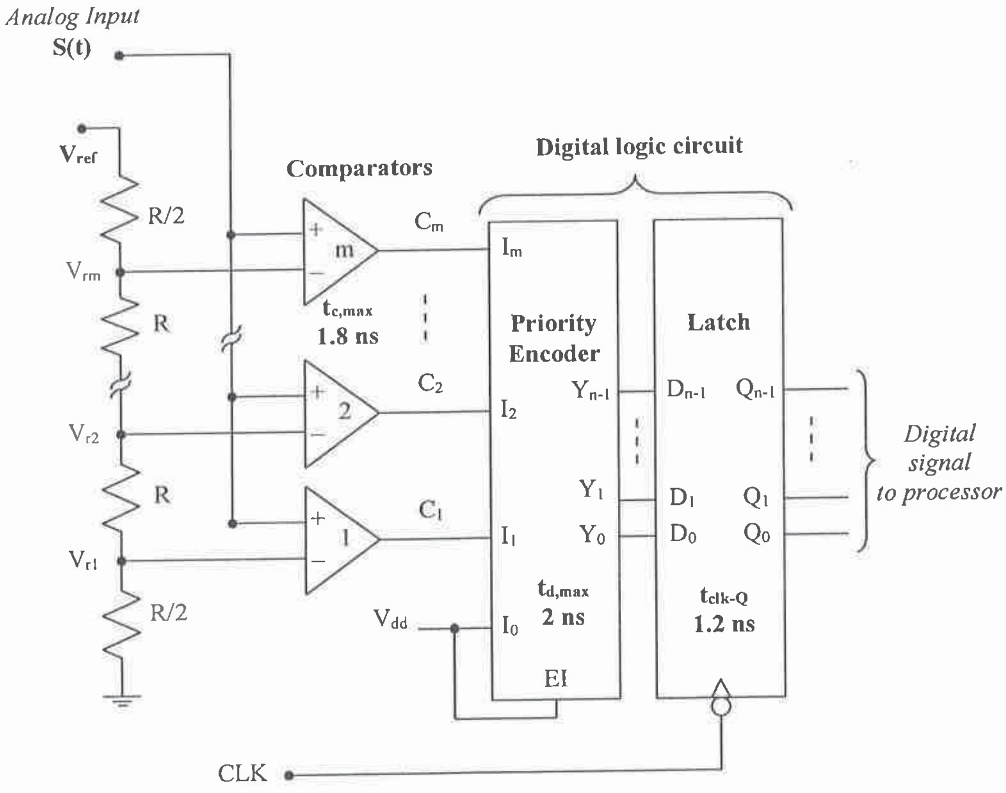
6. The circuit displayed in Figure P6 receives a rapidly changing audio signal S(t) and uses a three-stage n-bit analog-to-digital converter (ADC) to provide a digital signal to a processor. Maximum delays of major components of the ADC are also shown. The input signal amplitude range is $0 \leq S(t) \leq 3$ V.

3 pts (a) State the name of the type of ADC circuit used <u>and</u> state its main disadvantage and its main advantage.

6 pts (b) If $V_{ref} = 3.1$V, determine the minimum number of bits n required to code the digital signal to obtain a resolution of at least 0.025 V.

6 pts (c) If the ADC is designed with $n = 8$, what would be the value of the binary (hexadecimal) code sent to the processor when the amplitude of S(t) = 2 V?

5 pts (d) What is the maximum speed (frequency) of conversion of this ADC?



<u>Figure P6</u>

7. Figure P7 shows the basic diagram of a precision bridge rectifier for instrumentation applications. The OP amp is assumed to be ideal. The meter M has a coil resistance of $r = 100\ \Omega$ and provides a full-scale deflection when the *average current* through it is 2 mA.

8 pts (a) Find the value of R to provide a full-scale reading when the input voltage is a sine wave of amplitude equal to 5 V.

8 pts (b) At full-scale reading, and assuming the diodes have a 0.5 V forward voltage drop, evaluate how far the maximum value of V_C is from the *saturation level* of the OP amp.

4 pts (c) If an engineer decides to use diodes with a *peak reverse voltage* (PRV) rating equal to 1 V, determine if this rating is sufficient to prevent junction breakdown at full-scale reading.

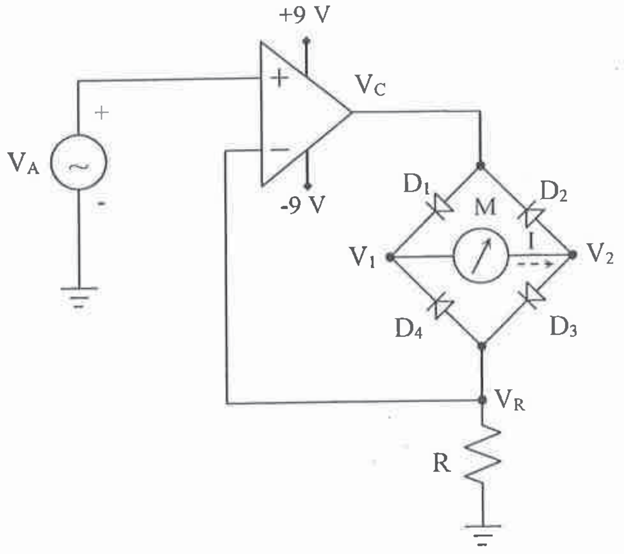


Figure P7

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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) $q = 1.6\text{x}10^{-19}$ C

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

(4) Decibel: 20 $\log_{10} (V_2/V_1)$ for a voltage ratio; 10 $\log_{10} (P_2/P_1)$ for a power ratio

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

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

(7) $\varepsilon_{SiO2} = 0.345\text{x}10^{-12}$ 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) $$\mu = \frac{v_{drift}}{\varepsilon}$$

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

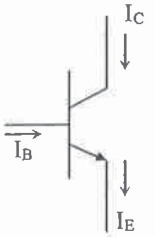
BJT relationships and model

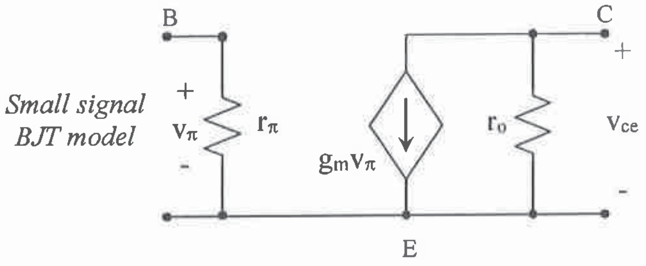
(26) $I_C = \beta I_B$ where $\beta = I_C/I_B$

(27) $I_E = I_B + I_C$

(28) $g_m = I_C/V_T$

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





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

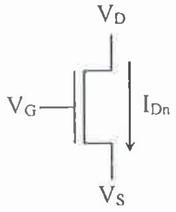
(34) $V_T=\Phi_{ms}+2\phi_F-\frac{1}{C_i}(Q_i+Q_d)$

MOSFET symbols, relationships and model

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

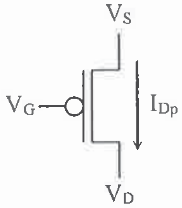
(36) $k_n = \mu_n C_{ox}(W/L)_n$

(37) $k_p = \mu_p C_{ox}(W/L)_p$



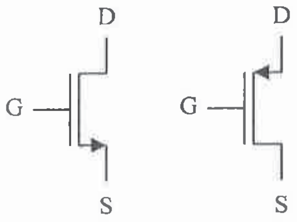
(38) $I_{Dn} = (k_n/2)\,(V_{GSn} - V_{tn})^2$ when $V_{DSn} > V_{GSn} - V_{tn}$

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

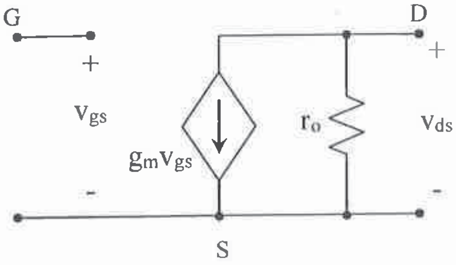


(40) $I_{Dp} = (k_p/2)\,(V_{GSp} - V_{tp})^2$ when $V_{DSp} < V_{GSp} - V_{tp}$

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



MOSFET small signal model



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

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

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

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