ELEG 646 - Spring 09
Electronic Device Principles
Final Examination

20 May 2010 NAME________________________________

Time Limit: 120 minutes

Closed Books and Notes. You may use your own calculator, but may not loan or borrow one (ask proctor if you have questions). Put expression in a final form as best you can.

Guidelines:

I. Full credit requires the final dimensions/ units for all numerical quantities that you calculate.

II. Show all work and calculations for full credit; accuracy to 2 significant figures is sufficient.

III. Assume that the material is silicon at room temperature (300 K), unless otherwise stated.

IV. At 300K temperature; thermal energy k_BT=0.026eV, silicon intrinsic concentration $n_i = 1\text{x}10^{10}\ \text{cm}^{-3}$, recombination lifetimes: $\tau_n, \tau_p = 1$ μsec; dielectric constant $\kappa_{Si} = 11.8$;

In general; permittivity of free space $\boldsymbol{\varepsilon}_o = 8.85\text{x}10^{-14}$ F/cm; electron charge $|q| = 1.6\text{x}10^{-19}$ Coul;

V. Equations:

$p_{op} = i\hbar d/dx$ $f_{FD}(E) = 1/[1 + \exp(E–E_F)/k_BT]$ $E = Q\ V$

$n = n_i\exp[(E_F–E_i)/k_BT]$. $p = n_i\exp[(E_i–E_F)/k_BT]$ $n_op_o = n_i^2$ $np = n_i^2e^{(Fn-Fp)/kBT}$

$n = N_C\exp[-(E_C-E_F)/k_BT]$ $N_C = 2.8\ \text{x}10^{19}\ \text{cm}^{-3}$ $p = N_V\exp[-(E_F-E_V)/k_BT]$ $N_V = 1.04\ \text{x}10^{19}\ \text{cm}^{-3}$

$J_n = q\mu_nn\mathcal{E} + qD_ndn/dx$ $J_p = q\mu_pp\mathcal{E} – qD_pdp/dx$ $\sigma_{elec} = q(n\mu_n + p\mu_p)$

$U_n = (n_p–n_{po})/\tau_n$ $U_p = (p_n–p_{no})/\tau_p$ $p' = p - p_o = g_{opt}\tau_p$ $n' = n - n_o = g_{opt}\tau_n$

$C_{dep} = \kappa_s\boldsymbol{\varepsilon}_o\ A/W$ $C_{diff} = qI\tau/k_BT$ $D/\mu = k_BT/q$ $L = \sqrt{(D\tau)}$

$\partial p/\partial t = -1/q\ \partial J_p/\partial x – p'/\tau_p$ $\partial n/\partial t = -1/q\ \partial J_n/\partial x – n'/\tau_n$;

$\partial p/\partial t = D_p\ \partial^2p/\partial x^2 – p'/\tau_p$ $\partial n/\partial t = D_n\ \partial^2n/\partial x^2 – n'/\tau_n$

$\varphi_{bi} = k_BT/q\ \ln(N_AN_D/n_i^2)$ $\varphi = (E_F-E_i)/q + \varphi_{ref}$ (φ_{ref} =constant or)) ; $\mathcal{E} = -d\varphi/dx$

$I = qA(D_pp_n/L_p + D_nn_p/L_n)[e^{qV/kT} – 1] = I_o[e^{qV/kT} – 1]$; $W_{dep} = [(2\kappa_s\boldsymbol{\varepsilon}_o/q)(1/N_A + 1/N_D)(\varphi_{bi} - V_F)]^{1/2}$

$\mathcal{E}_{max}= 2(\varphi_{bi}– V_F)/W_{dep}$ $p_n(x_{no}) = p_{no}(x_{no})e^{qVf/kT}$; $n_p(-x_{po}) = n_{po}(-x_{po})e^{qVf/kT}$

VI. Equations: (note, kT, ε are on page 1)

$n = n_i \exp[(E_F - E_i)/k_B T]$. $p = n_i \exp[(E_i - E_F)/k_B T]$

$J_n = q\mu_n n\mathcal{E} + qD_n dn/dx$ $J_p = q\mu_p p\mathcal{E} - qD_p dp/dx$

$U_n = (n_p - n_{po})/\tau_n$ $U_p = (p_n - p_{no})/\tau_p$

$C = \boldsymbol{\varepsilon}_s / W$

One-sided step junction:

$C = \boldsymbol{\varepsilon}_s / W$; $\phi_{bi} = (k_B T/q)\ln[N_A N_D / n_i^2]$

Breakdown (for n^+-p diode)

$\mathcal{E}_{max} = [2qN_A|V_R|/\varepsilon_s]^{1/2}$; $BV = \varepsilon_s \mathcal{E}_{crit}^2 / 2qN_A$

Schottky junctions:

$I_F = A_J A^* T^2 \exp(-q\varphi_B/kT)\,[\exp(qV/\eta kT) - 1]$; where η = ideality factor

pnp transistors:

$I_E = I_C + I_B$; $I_C = \boldsymbol{\alpha}_F I_E + I_{CBO}$ $I_C = \boldsymbol{\beta} I_B + I_{CEO}$ $\boldsymbol{\alpha_F = \gamma\, \alpha_T\, M}$

$I_{pE} = A_E q^2 n_i^2 D_p / Q_{B0} \exp[(qV_{BE})/k_B T]$ $Q_{B0} = q \int_0^{WB} N_D(x)dx = q\,GN$; (GN = Gummel number)

$\boldsymbol{\alpha_F = \gamma\, \alpha_T\, M}$

Ebers-Moll model (for pnp): $I_E = I_{ES}/p_{no}(\Delta p_E - \alpha_F \Delta p_C)$; $I_C = I_{CS}/p_{no}(\alpha_R\, \Delta p_E - \Delta p_C)$

$\Delta p_E = p_{no}(e^{qVEB/kT} - 1)$ $\Delta p_C = p_{no}(e^{qVCB/kT} - 1)$

Reciprocity: $\alpha_F I_{ES} = \alpha_R I_{CS} = I_S$

Junction Field Effect Transistors:

pFET: $V_P = qN_A a^2/2\varepsilon_s$ or   nFET: $V_P = qN_D a^2/2\varepsilon_s$ $\varphi_{bi} = (k_B T/q)\ln(N_A N_D/n_i^2)$

cutoff frequency: $f_T = g_m/2\pi C_{GS}$

Notes:

C_B = doping concentration in the bulk $\equiv N_A$ or N_D

$\varphi_B = \varphi_{bi}$ = built-in voltage (contact potential)

A_J = junction area

TABLE 4.2

IMPORTANT FORMULAS IN SEMICONDUCTOR PHYSICS
Complete ionization of impurities
Thermal equilibrium

Charge neutrality	$\rho = q(p - n + N_D - N_A) = 0$
Equilibrium condition	$pn = n_i^2$
Fermi-Dirac distribution function	$f(E) = \dfrac{1}{1 + e^{(E-E_F)/kT}}$
Carrier concentrations in non-degenerate semiconductors:	$n = N_c e^{-(E_c-E_F)/kT} = n_i e^{(E_F-E_i)/kT}$ $p = N_v e^{-(E_F-E_v)/kT} = n_i e^{(E_i-E_F)/kT}$
In the extrinsic case, $\lvert N_D - N_A \rvert \gg n_i$:	$n_n \doteq N_D - N_A \quad p_p \doteq N_A - N_D$ $p_n \doteq \dfrac{n_i^2}{N_D - N_A} \quad n_p \doteq \dfrac{n_i^2}{N_A - N_D}$

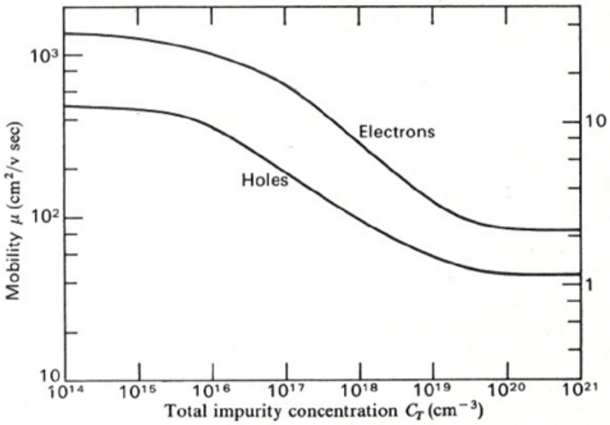

Fig. 4.11 The effect of the total ionized impurity concentration on the mobility of carriers in silicon at room temperature.[4] Also shown are the corresponding values of diffusivity.

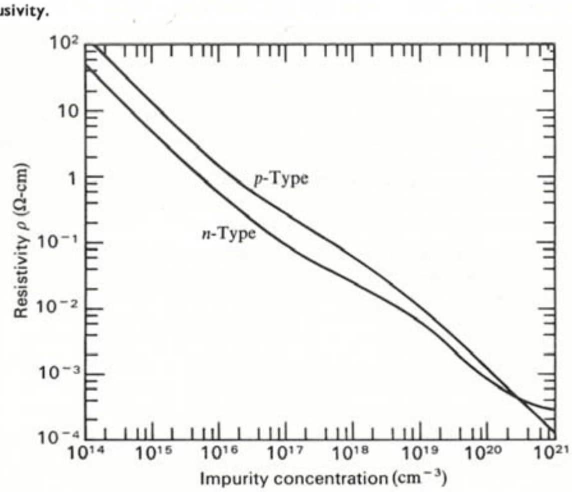

Fig. 4.14 Resistivity of silicon at room temperature as a function of acceptor or donor impurity concentration.[6]

TABLE 3.1 Schottky Barriers to Silicon [10]
($q\chi$ for Silicon = 4.05 eV)

Silicon Type	Metal	$q\Phi_M$(eV)	$q\phi_B$(eV)
n	Al	4.1	0.69
p	Al	—	0.38
n	Pt	5.3	0.85
p	Pt	—	0.25
n	W	4.5	0.65
n	Au	4.75	0.79
p	Au	—	0.25

TABLE 6.1

IMPORTANT FORMULAS FOR ONE-SIDED STEP JUNCTIONS

Built-in voltage	$\phi_B \cong 2\frac{kT}{q}\ln\frac{C_B}{n_i}$
Depletion region width	$W = \sqrt{\frac{2K_s\epsilon_0[\phi_B \pm \lvert V_J\rvert]}{qC_B}}$ where $\left.\begin{matrix}+\text{: reverse}\\-\text{: forward}\end{matrix}\right\}$ bias
Maximum electric field	$\mathscr{E}_{\max} = 2\frac{\phi_B \pm \lvert V_J\rvert}{W}$
Capacitance per unit area	$C = \frac{K_s\epsilon_0}{W}$
Reverse current	$I_R = I_{\text{gen}} + I_{\text{diff}}$ $I_{\text{gen}} = \frac{1}{2}q\frac{n_i}{\tau}WA_J$ $I_{\text{diff}} = qD\frac{n_i^2}{C_BL}A_J$
Forward current	$I_F = I_{\text{rec}} + I_{\text{diff}}$ $I_{\text{rec}} = -\frac{1}{2}q\frac{n_i}{\tau}We^{q\lvert V_F\rvert/2kT}A_J$ $I_{\text{diff}} = -qD\frac{n_i^2}{C_BL}e^{q\lvert V_F\rvert/kT}A_J$
Avalanche breakdown voltage	$BV = \frac{K_s\epsilon_0\mathscr{E}_{\text{crit}}^2}{2qC_B}$

TABLE 7.1

IMPORTANT FORMULAS FOR JUNCTION TRANSISTORS

	pnp	*npn*
Current gain	$\alpha \equiv h_{FB} \equiv \frac{I_C}{I_E} \quad \beta \equiv h_{FE} \equiv \frac{I_C}{I_B} \quad \beta = \frac{\alpha}{1-\alpha}$ $\alpha = \gamma\alpha_T$ [See footnote on page 219.]	
Transport factor	$\alpha_T \cong 1 - \frac{1}{2}\left(\frac{W_B}{L_{pB}}\right)^2 \cong 1 - \frac{t_{tr}}{\tau_p}$	$\alpha_T \cong 1 - \frac{1}{2}\left(\frac{W_B}{L_{nB}}\right)^2 \cong 1 - \frac{t_{tr}}{\tau_n}$
Emitter efficiency	$\gamma = \frac{1}{1 + \frac{B}{E} + \frac{1}{2}\sqrt{\frac{qBA_J}{I_C}}R}$ $R = \frac{W_{EB}}{\tau_o} + s_o\frac{A_s}{A_J}$ $B \equiv \frac{N_{DB}W_B}{D_{pB}}$ $E \equiv \frac{N_{AE}W_E}{D_{nE}}$	$B \equiv \frac{N_{AB}W_B}{D_{nB}}$ $E \equiv \frac{N_{DE}W_E}{D_{pE}}$
Transit time	$t_{tr} = \frac{W_B^2}{2D_{pB}}$;	$t_{tr} = \frac{W_B^2}{2D_{nB}}$
Base resistance	$r_B' = \frac{1}{12}\frac{\bar{\rho}_B}{W_B}\frac{L}{Z}$ for stripe geometry	
Leakage currents	$I_{CEO} = \frac{I_{CBO}M}{1 - \gamma\alpha_T M}$	
Maximum voltages	$BV_{CEO} \cong \frac{BV_{CBO}}{\sqrt[n]{h_{FE}}}$	
Minimum voltage	$V_{CE}(\text{sat}) = \pm\left\{\frac{kT}{q}\left\lvert\ln\frac{\alpha_R\left[1 - \frac{I_C}{I_Bh_{FE}}\right]}{1 + \frac{I_C(1-\alpha_R)}{I_B}}\right\rvert + \lvert I_Er_{SE}\rvert + \lvert I_Cr_{SC}\rvert\right\}$ $-pnp$ $\quad +npn$	

note for Table 8.1, $d = 2a$*(full channel thickness)* the symbol ϕ_B is the magnitude of built in voltage

TABLE 8.1
IMPORTANT FORMULAS FOR JUNCTION FIELD-EFFECT TRANSISTORS

	n-channel $V_D > 0,\ V_G < 0$; I_D flows from drain to source	p-channel $V_D < 0,\ V_G > 0$; I_D flows from source to drain
Current-voltage characteristics	$I_D = G_o\left\{V_D - \frac{2}{3}\sqrt{\frac{8K_s\epsilon_0}{qN_Dd^2}} \times [(V_D + \phi_B - V_G)^{3/2} - (\phi_B - V_G)^{3/2}]\right\}$ where $G_o \equiv \frac{Z}{L}q\mu_n N_D d$	$I_D = G_o\left\{-V_D - \frac{2}{3}\sqrt{\frac{8K_s\epsilon_0}{qN_Ad^2}} \times [(V_G + \phi_B - V_D)^{3/2} - (V_G + \phi_B)^{3/2}]\right\}$ where $G_o \equiv \frac{Z}{L}q\mu_p N_A d$
Saturation voltage	$V_{D\text{sat}} = \frac{qN_Dd^2}{8K_s\epsilon_0} - \phi_B + V_G$	$V_{D\text{sat}} = -\frac{qN_Ad^2}{8K_s\epsilon_0} + \phi_B + V_G$
Turn-off voltage	$V_T = -\frac{qN_Dd^2}{8K_s\epsilon_0} + \phi_B$	$V_T = \frac{qN_Ad^2}{8K_s\epsilon_0} - \phi_B$
Conductance (linear region) Transconductance (saturation)	$\left.\begin{matrix} g_{\text{linear}} \\ g_{m\text{sat}} \end{matrix}\right\} = G_o\left[1 - \sqrt{\frac{8K_s\epsilon_0(\phi_B - V_G)}{qN_Dd^2}}\right]$	$\left.\begin{matrix} g_{\text{linear}} \\ g_{m\text{sat}} \end{matrix}\right\} = G_o\left[1 - \sqrt{\frac{8K_s\epsilon_0(\phi_B + V_G)}{qN_Ad^2}}\right]$
Saturation current	$I_{D\text{sat}} = G_o\left\{\left[\frac{2}{3}\sqrt{\frac{8K_s\epsilon_0(\phi_B - V_G)}{qN_Dd^2}} - 1\right] \times (\phi_B - V_G) + \frac{1}{3}\frac{qN_Dd^2}{8K_s\epsilon_0}\right\}$	$I_{D\text{sat}} = G_o\left\{\left[\frac{2}{3}\sqrt{\frac{8K_s\epsilon_0(\phi_B + V_G)}{qN_Ad^2}} - 1\right] \times (\phi_B + V_G) + \frac{1}{3}\frac{qN_Ad^2}{8K_s\epsilon_0}\right\}$
Maximum frequency	$f_o = \frac{g_m}{C_G} \leq \frac{q\mu_n N_D d^2}{2K_s\epsilon_0 L^2}$	$f_o = \frac{g_m}{C_G} \leq \frac{q\mu_p N_A d^2}{2K_s\epsilon_0 L^2}$
Effect of series resistances	Linear region $g(\text{obs}) = \frac{g}{1 + (R_s + R_d)g}$ Saturation region $g_{m\text{sat}}(\text{obs}) = \frac{g_{m\text{sat}}}{1 + R_s g_{m\text{sat}}}$	

TABLE 8.3 Formulas for the Oxide-Silicon System

	***p*-type substrate (*n*-channel)**	***n*-type substrate (*p*-channel)**
Flat-band voltage (*Equation 8.4.6*)	$V_{FB} = \Phi_{MS} - \frac{Q_f}{C_{ox}} - \frac{1}{C_{ox}}\int_0^{x_{ox}} \frac{x}{x_{ox}}\rho(x)\,dx$	
Bulk potential (*Equation* 4.2.9)	$\phi_p = -\frac{kT}{q}\ln\left(\frac{N_a}{n_i}\right)$	$\phi_n = \frac{kT}{q}\ln\left(\frac{N_d}{n_i}\right)$
Surface potential for strong inversion (*Table 3.1*) Thermal equilibrium	$\phi_s = \lvert\phi_p\rvert$ $\phi_s - \phi_p = 2\lvert\phi_p\rvert$	$\phi_s = -\lvert\phi_n\rvert$ $\phi_s - \phi_n = -2\lvert\phi_n\rvert$
With bias $(V_C - V_B) = V_{CB}$	$\phi_s = \lvert\phi_p\rvert + V_{CB}$	$\phi_s = -\lvert\phi_n\rvert - \lvert V_{CB}\rvert$
Maximum depletion width, $x_{d\max}$ (*Equation 8.3.6*) Thermal equilibrium	$\sqrt{\frac{4\epsilon_s\lvert\phi_p\rvert}{qN_a}}$	$\sqrt{\frac{4\epsilon_s\lvert\phi_n\rvert}{qN_d}}$
With bias V_{CB} (*Equation 8.3.8*)	$\sqrt{\frac{2\epsilon_s(2\lvert\phi_p\rvert + V_{CB})}{qN_a}}$	$\sqrt{\frac{2\epsilon_s(2\lvert\phi_n\rvert + \lvert V_{CB}\rvert)}{qN_d}}$
Work-function difference, Φ_{MS}	$\Phi_M - (\mathrm{X} + E_g/2q + \lvert\phi_p\rvert)$	$\Phi_M - (\mathrm{X} + E_g/2q - \lvert\phi_n\rvert)$
Threshold voltage V_T (arbitrary reference) (*Equation 8.3.18*)	$V_{FB} + V_C + 2\lvert\phi_p\rvert + \frac{1}{C_{ox}}\sqrt{2\epsilon_s qN_a(2\lvert\phi_p\rvert + V_C - V_B)}$	$V_{FB} + V_C - 2\lvert\phi_n\rvert - \frac{1}{C_{ox}}\sqrt{2\epsilon_s qN_d(2\lvert\phi_n\rvert + V_B - V_C)}$

TABLE 9.4 MOSFET Equations

Basic Electrostatic Equations

n-channel	*p*-channel
Depletion charge density at threshold (Equation 8.3.9) $Q_d = -qN_a x_{dmax} = -\sqrt{2\epsilon_s qN_a(2\lvert\phi_p\rvert + \lvert V_{SB}\rvert)}$	$Q_d = +qN_a x_{dmax} = +\sqrt{2\epsilon_s qN_a(2\lvert\phi_p\rvert + \lvert V_{SB}\rvert)}$
Flatband voltage (Equation 8.5.6) $V_{FB} = \Phi_{MS} - \frac{Q_f}{C_{ox}} - \frac{1}{C_{ox}}\int_0^{x_{ox}} \frac{x\rho(x)}{x_{ox}}dx$	
Threshold voltage (Equation 8.3.18) $V_T = V_{FB} + V_S + 2\lvert\phi_p\rvert + \frac{\lvert Q_d\rvert}{C_{ox}}$	$V_T = V_{FB} - V_S - 2\lvert\phi_n\rvert - \frac{\lvert Q_d\rvert}{C_{ox}}$
Threshold-voltage shift with body bias (Equation 9.1.11) $\Delta V_T = \frac{\sqrt{2\epsilon_s qN_a}}{C_{ox}}\left(\sqrt{2\lvert\phi_p\rvert + \lvert V_{SB}\rvert} - \sqrt{2\lvert\phi_p\rvert}\right)$	$\Delta V_T = -\frac{\sqrt{2\epsilon_s qN_a}}{C_{ox}}\left(\sqrt{2\lvert\phi_p\rvert + \lvert V_{SB}\rvert} - \sqrt{2\lvert\phi_p\rvert}\right)$
Long-Channel Current-Voltage Equations	
Linear-region drain current (Equation 9.1.5) $I_D = \mu_n C_{ox}\frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$	$I_D = -\mu_p C_{ox}\frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$
Long-channel saturation drain voltage $V_{Dsat} = (V_{GS} - V_T)$	
Saturation-region drain current (Equation 9.1.6) $I_{Dsat} = \mu_n C_{ox}\frac{W}{2L}(V_{GS} - V_T)^2$	$I_{Dsat} = -\mu_p C_{ox}\frac{W}{2L}(V_{GS} - V_T)^2$
Channel-length modulation (Equation 9.1.10) $I_{Dsat} = \mu_n C_{ox}\frac{W}{2L}(V_{GS} - V_T)^2\left(1 + \frac{V_{DS}}{V_A}\right)$	$I_{Dsat} = -\mu_p C_{ox}\frac{W}{2L}(V_{GS} - V_T)^2\left(1 - \frac{V_{DS}}{V_A}\right)$
Saturation-region transconductance (Equation 9.1.37) $g_{msat} = \mu_n C_{ox}\frac{W}{L}(V_{GS} - V_T) = \frac{2I_{Dsat}}{(V_{GS} - V_T)}$	$g_{msat} = -\mu_p C_{ox}\frac{W}{L}(V_{GS} - V_T) = -\frac{2I_{Dsat}}{(V_{GS} - V_T)}$
Long-Channel Current-Voltage Equations with Substrate Charge	
Linear-region drain current (Equation 9.1.17) $I_D = \mu_n C_{ox}\frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{\alpha V_{DS}^2}{2}\right]$	$I_D = -\mu_p C_{ox}\frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{\alpha V_{DS}^2}{2}\right]$
Saturation drain voltage (Equation 9.1.18) $V_{Dsat} = \frac{(V_{GS} - V_T)}{\alpha}$	
Saturation-region drain current (Equation 9.1.19) $I_{Dsat} = \mu_n C_{ox}\frac{W}{2\alpha L}(V_{GS} - V_T)^2$	$I_{Dsat} = -\mu_p C_{ox}\frac{W}{2\alpha L}(V_{GS} - V_T)^2$
Short-Channel Current-Voltage Equations	
Effective vertical field (Equation 9.2.3) $\mathscr{E}_{eff} = \frac{(V_{GS} - V_T)}{6x_{ox}} + \frac{(V_T + V_Z)}{3x_{ox}}$	$\mathscr{E}_{eff} = \frac{(V_{GS} - V_T)}{6x_{ox}} + \frac{(V_T - V_Z)}{3x_{ox}}$
Effective mobility (Equation 9.2.4) $\mu_{eff} = \frac{\mu_0}{1 + (\mathscr{E}_{eff}/\mathscr{E}_0)^\nu}$	$\mu_{eff} = \frac{\mu_0}{1 + (-\mathscr{E}_{eff}/\mathscr{E}_0)^\nu}$
Saturation $\mathscr{E}$-field (Equation 9.2.7) $\mathscr{E}_{sat} = 2v_{sat}/\mu_{eff}$	$\mathscr{E}_{sat} = -2v_{sat}/\mu_{eff}$
Linear-region drain current (Equation 9.2.9) $I_D = \mu_{eff} C_{ox}\frac{W}{L}\left[(V_{GS} - V_T) - \frac{V_{DS}}{2}\right]\frac{V_{DS}}{1 + (V_{DS}/\mathscr{E}_{sat}L)}$	$I_D = -\mu_{eff} C_{ox}\frac{W}{L}\left[(V_{GS} - V_T) - \frac{V_{DS}}{2}\right]\frac{V_{DS}}{1 + (V_{DS}/\mathscr{E}_{sat}L)}$
Saturation drain voltage (Equation 9.2.11) $V_{Dsat} = \frac{(V_{GS} - V_T)\mathscr{E}_{sat}L}{V_{GS} - V_T + \mathscr{E}_{sat}L}$	
Saturation-region drain current (Equation 9.2.10) $I_{Dsat} = WC_{ox}v_{sat}(V_{GS} - V_T - V_{Dsat})$	$I_{Dsat} = -WC_{ox}v_{sat}(V_{GS} - V_T - V_{Dsat})$

TABLE 1.3 Properties of Semiconductors and Insulators (at 300 K Unless Otherwise Noted)

Property	Symbol	Units	Si	Ge	GaAs	GaP	SiO_2	Si_3N_4
Crystal structure			Diamond	Diamond	Zincblende	Zincblende	[Amorphous for most IC applications]	
Atoms per unit cell			8	8	8	8		
Atomic number	Z		14	32	31/33	31/15	14/8	14/7
Atomic or molecular weight	MW	g/g-mole	28.09	72.59	144.64	100.70	60.08	140.28
Lattice constant	a_0	nm	0.54307	0.56575	0.56532	0.54505		0.775
Atomic or molecular density	N_0	cm^{-3}	5.00×10^{22}	4.42×10^{22}	2.21×10^{22}	2.47×10^{22}	2.20×10^{22}	1.48×10^{22}
Density		$g\ cm^{-3}$	2.328	5.323	5.316	4.13	2.19	3.44
Energy gap 300K	E_g	eV	1.124	0.67	1.42	2.24	~8 to 9	4.7
0K	E_g	eV	1.170	0.744	1.52	2.40		
Temperature dependence	$\Delta E_g/\Delta T$	$eV\ K^{-1}$	-2.7×10^{-4}	-3.7×10^{-4}	-5.0×10^{-4}	-5.4×10^{-4}		
Relative permittivity	ϵ_r		11.7	16.0	13.1	10.2	3.9	7.5
Index of refraction	n		3.44	3.97	3.3	3.3	1.46	2.0
Melting point	T_m	°C	1412	937	1237	1467	~1700	~1900
Vapor pressure		Torr (mm Hg) (at °C)	10^{-7} (1050) 10^{-5} (1250)	10^{-9} (750) 10^{-7} (880)	1 (1050) 100 (1220)	10^{-6} (770) 10^{-4} (920)		
Specific heat	C_p	$J\ (g\ K)^{-1}$	0.70	0.32	0.35		1.4	0.17
Thermal conductivity	κ	$W(cm\ K)^{-1}$	1.412	0.606	0.455	0.97	0.014	0.185(?)
Thermal diffusivity	D_{th}	$cm^2\ s^{-1}$	0.87	0.36	0.44		0.004	0.32(?)
Coefficient of linear thermal expansion	α'	K^{-1}	2.5×10^{-6}	5.7×10^{-6}	5.9×10^{-6}	5.3×10^{-6}	5×10^{-7}	2.8×10^{-6}
Intrinsic carrier concentration*	n_i	cm^{-3}	1.45×10^{10}	2.4×10^{13}	9.0×10^{6}			
Lattice mobility								
Electron	μ_n	$cm^2(V\ s)^{-1}$	1417	3900	8800	300	20	
Hole	μ_p	$cm^2(V\ s)^{-1}$	471	1900	400	100	$\sim 10^{-8}$	
Effective density of states								
Conduction band	N_c	cm^{-3}	2.8×10^{19}	1.04×10^{19}	4.7×10^{17}			
Valence band	N_v	cm^{-3}	1.04×10^{19}	6.0×10^{18}	7.0×10^{18}			
Electric field at breakdown	$\mathscr{E}_1$	$V\ cm^{-1}$	3×10^{5}	8×10^{4}	3.5×10^{5}		$6-9 \times 10^{6}$	
Effective mass								
Electron	m_n^*/m_0		1.08^a 0.26^b	0.55^a 0.12^b	0.068	0.5		
Hole	m_p^*/m_0		0.81^a 0.386^b	0.3	0.5	0.5		
Electron affinity	qX	eV	4.05	4.00	4.07	~4.3	1.0	
Average energy loss per phonon scattering		eV	0.063	0.037	0.035			
Optical phonon mean-free path								
Electron	λ_{ph}	nm	6.2	6.5	3.5			
Hole	λ_{ph}	nm	4.5	6.5	3.5			