MOS Device: Basics

- MOSFET & Modeling -

Renesas Design Vietnam Co., Ltd.
Phuoc Tran, Nguyen Phuoc Nguyen, RVC Training Center

Appendix

October 11, 2010 Rev. 0.00

00000-A

Appendix

1. List of Symbols
2. Physical Constant
3. Properties of Si, Ge, GaAs and SiO2
4. Physical Parameters of Silicon
5. Equations in Semiconductor Physics
6. Equations in PN-Diode
7. Equations in MOS-Diode
8. Equations in MOSFET (Simple)
9. Equations in MOSFET (First-order)
10. High-K Materials

1. List of symbols

(After Textbook of Sze)

Symbol	Description	Unit
a	Lattice constant	m
c	Speed of light in vacuum	m/s
C	Capacitance	F
E	Energy	eV
E_C	Bottom of conduction band	eV
E_F	Fermi energy level	eV
Eg	Energy bandgap	eV
E_V	Top of valence band	eV
F(E)	Fermi-Dirack distribution function	
I	Current	A
J	Current density	A/m2
k	Boltzmann constant	J/K
kT	Thermal energy	eV
L	Length (channel length)	m
mo	Electron rest mass	kg
m*	Effective mass	kg
n	Density of free electron	m-3
ni	Intrinsic density	m-3
N	Doping concentration	m-3
NA	Accepter impurity density	m-3
NC	Effective density states in conduction band	m-3

Continued…

Symbol	Description	Unit
ND	Donor impurity concentration	m-3
NV	Effective density of states in valence band	m-3
p	Density of free hole	m-3
q	Magnitude of electronic charge	C
R	Resistance	Ω
t	time	s
T	Absolute temperature	K
v	Carrier velocity	m/s
vth	Thermal velocity	m/s
V	Voltage	V
Vbi	Built-in voltage	V
VFB	Flat band voltage	V
Vth	Threshold voltage	V
ε o	Permittivity in vacuum	F/m
ε s or ε si	Semiconductor permittivity	F/m
ε I or ε ox	Insulator permittivity	F/m
μ n	Electron mobility	m2/V.s
μ p	Hole mobility	m2/V.s
ρ	Resistivity	Ω-m
ϕ m	Metal work function	V
Ω	Ohm	Ω

2. Physical constant

Quantity	Symbol	Value
Elementary charge	q	1.60×10^{-19} C
Electron rest mass	mo	0.911×10^{-30} kg
Electron volt	eV	1.60×10^{-19} J
Permittivity in vacuum	ε o	8.85×10^{-12} F/m
Speed of light	c	3.00×10^{8} m/s
Thermal voltage @300K	kT/q	0.0259 V

3. Properties of Ge, Si, GaAs and SiO2

	Ge	Si	GaAs	SiO_2
Atomic or molecular weight	72.60	28.09	144.63	60.08
Atoms or molecules/cm^3	4.42×10^{22}	5.00×10^{22}	2.21×10^{22}	2.3×10^{22}
Crystal structure	Diamond, 8 atoms/unit cell	Diamond, 8 atoms/unit cell	Zinc-blende, 8 atoms/unit cell	Random network of SiO_4, tetrahedra, 50% covalent, 50% ionic bonding
Lattice constant (A)	5.66	5.43	5.65	...
Density, ρ (g/cm^3)	5.32	2.33	5.32	2.27
Energy gap (ev)	0.67	1.11	1.40	~8
Effective density of states conduction band N_c (cm^{-3}) valence band Nv (cm^{-3})	1.04×10^{19} 6.0×10^{18}	2.8×10^{19} 1.04×10^{19}	4.7×10^{17} 7.0×10^{18}	...
Intrinsic carrier concentration n_i (cm^{-3})	2.4×10^{13}	1.45×10^{10}	$\sim 9 \times 10^{6}$	...

(After Textbook of Grove)

Continued …..

Lattice (intrinsic) mobilities (cm^2/v sec) electrons holes	3900 1900	1350 480	8600 250	Insulator; $\rho > 10^{16}$ Ω-cm at 300°K
Dielectric constant	16.3	11.7	12	3.9
Breakdown field (v/μ)	~8	~30	~35	~600
Melting point (°C)	937	1415	1238	~1700
Vapor pressure (Torr)	10^{-7} at 880°C 10^{-9} at 750°C	10^{-5} at 1250°C 10^{-7} at 1050°C	1 at 1050°C 100 at 1220°C	10^{-3} at 1450°C 10^{-1} at 1700°C
Specific heat, C_p (Joule/g°C)	0.31	0.7	0.35	1.0
Thermal conductivity, K_{th} (watt/cm°C)	0.6	1.5	0.81	0.014
Thermal diffusivity $\kappa = \frac{K_{th}}{_{\rho}C_p}\left(\frac{cm^2}{sec}\right)$	0.36	0.9	0.44	0.006
Linear coefficient of thermal expansion $\frac{\Delta L}{L\Delta T}\left(\frac{1}{°C}\right)$	5.8×10^{-6}	2.5×10^{-6}	5.9×10^{-6}	0.5×10^{-6}

4. Key Physical Parameters of Silicon

Molecular Number (/cm3)	$5.00X10^{22}$
Crystal Structure	Diamond
Lattice Constant a (nm)	0.543
Material Density (g/cm3)	2.33
Energy Gap (eV)	1.11
Density of State: Conduction Band Nc(cm-3) Valence Band Nv(cm-3)	$2.8X10^{19}$ $1.04X10^{19}$
Intrinsic Carrier Density ni (cm-3)	$1.45X10^{10}$
Intrinsic Carrier Mobility: Elec. (cm2/V.sec) Hole (cm2/V.sec)	1350 480
Permittivity ε (si)	11.7
Thermal Conductance kth(W/cm.℃)	1.5
Thermal Expansion Constant (/℃)	$2.5X10^{-6}$
Melting Temperature (℃)	1415

5. Equations of Semiconductor Physics

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: In the extrinsic case, $\lvert N_D - N_A \rvert \geq n_i$:	$n = N_c e^{-(E_c - E_F)/kT} = n_i e^{(E_F - E_i)/kT}$ $P = N_v e^{-(E_F - E_v)/kT} = n_i e^{(E_i - E_F)/kT}$ $n_n \equiv N_D - N_A \quad P_p \equiv N_A - N_D$ $P_n \equiv \dfrac{n_i^2}{N_D - N_A} \quad n_p \equiv \dfrac{n_i^2}{N_A - N_D}$

(After Textbook of Grove)

6. Equations of PN-Diode

Built-in voltage	$\phi_B \cong 2\frac{kT}{q}\ln\frac{C_B}{n_i}$
Depletion region width	$W = \sqrt{\frac{2K_S\varepsilon_0[\phi_B \pm \lvert V_J \rvert]}{qC_B}}$ where $\left.\begin{matrix} +\text{: reverse} \\ -\text{: forward} \end{matrix}\right\}$ bias
Maximum electric field	$\varepsilon_{max} = 2\frac{\phi_B \pm \lvert V_J \rvert}{W}$
Capacitance per unit area	$C = \frac{K_S\varepsilon_0}{W}$
Reverse current	$I_R = I_{gen} + I_{diff}$ $I_{gen} = \frac{1}{2}q\frac{n_i}{\tau}WA_J,\ I_{diff} = qD\frac{n_i^2}{C_BL}A_J$
Forward current	$I_F = I_{rec} + I_{diff}$ $I_{rec} = -\frac{1}{2}q\frac{n_i}{\tau}We^{q\lvert V_F \rvert/2kT}A_J,\ I_{diff} = -qD\frac{n_i^2}{C_BL}e^{q\lvert V_F \rvert/kT}A_J$
Avalanche breakdown voltage	$BV = \frac{K_S\varepsilon_0 E^2_{crit}}{2qC_B}$

(After Textbook of Grove)

7. Equations of MOS-Diode

Metal and semiconductor work-function difference (ϕ_{MS})	$\phi_{MS} = \chi_M - \left[\chi_{Si} + E_g(Si) - \frac{kT}{q} \ln\left(\frac{N_C}{N_A} \right) \right]$
Flat-band Voltage (V_{FB})	$V_{FB} = \phi_{MS} - \frac{Q_{SS}}{C_O}$
Physical Threshold Voltage (Vth)	$V_{th} = V_{FB} + 2\phi_F \frac{Q_B}{C_O}, \quad \phi_F = \frac{kT}{q} \ln\left(\frac{N_A}{n_i} \right), \quad Q_B = \sqrt{2\varepsilon_S q N_A (2\phi_F)}$
MOS Capacitance at Accumulation Condition	$C_{Acc} = C_O$
MOS **Capacitance at Flat-Band Condition**	$C_{FB} = C_O \frac{1}{1 + \frac{\varepsilon_S / L_D}{\varepsilon_{OX} / T_{OX}}}, \quad L_D = \sqrt{\frac{kT\varepsilon_S}{q^2 N_A}}$
MOS **Capacitance at Inversion Condition**	$C_{Inv} = C_O \frac{}{1 + \frac{\varepsilon_S / W_m}{\varepsilon_{OX} / T_{OX}}}, \quad W_m = \sqrt{\frac{4kT\varepsilon_S \ln(N_A / n_i)}{q^2 N_A}}$

8. Equations of MOSFET (simple)

	Linear region	Saturation region
Current-voltage characteristics	$I_{ds} = \frac{W}{L}\mu_n C_o\left(V_g - V_{th} - \frac{V_d}{2}\right)V_d$	$I_{ds} = \frac{1}{2}\frac{W}{L}\mu_n C_o\left(V_g - V_{th}\right)^2$
Saturation voltage	$V_{Dsat} = V_g - V_{th}$	———
Drain conductance	$g_d = \frac{1}{2}\frac{W}{L}\mu_n C_o\left(V_g - V_{th} - V_d\right)$	$g_d = 0$
Mutual conductance	$g_m = \frac{W}{L}\mu_n C_o V_d$	$g_m = \frac{W}{L}\mu_n C_o\left(V_g - V_{th}\right)$
Max. frequency	$f_O = \frac{g_m}{C_G} = \frac{\mu_n V_d}{L^2}$	$f_O = \frac{g_m}{C_G} = \frac{\mu_n\left(V_g - V_{th}\right)}{L^2}$

9. Equations of MOSFET (First-order)

	n-channel $V_D > 0$, $V_G > V_T$, I_D flows from source to drain.	n-channel $V_D > 0$, $V_G > V_T$, I_D flows from drain to source.
Current-voltage characteristics	$I_D = \frac{Z}{L}\mu_n C_o \left\{ \left[V_G - V_{FB} - 2\phi_{Fp} - \frac{V_D}{2} \right] V_D - \frac{2}{3}\frac{\sqrt{2K_s\epsilon_o q N_A}}{C_o}\left[(V_D + 2\phi_{Fp})^{\frac{3}{2}} - (2\phi_{Fp})^{\frac{3}{2}} \right] \right\}$	$I_D = \frac{Z}{L}\mu_n C_o \left\{ \left[V_G - V_{FB} - 2\phi_{Fn} - \frac{V_D}{2} \right] V_D - \frac{2}{3}\frac{\sqrt{2K_s\epsilon_o q N_D}}{C_o}\left[\lvert V_D + 2\phi_{Fn}\rvert^{\frac{3}{2}} - \lvert 2\phi_{Fn}\rvert^{\frac{3}{2}} \right]\right.$
Saturation voltage	$V_{Dsat} = V_G - V_{FB} - 2\phi_{Fp} + \frac{K_s\epsilon_o q N_A}{C_o^2}\left[1 - \sqrt{1 + \frac{2C_o^2 (V_G - V_{FB})}{K_s\epsilon_o q N_A}} \right]$	$V_{Dsat} = V_G - V_{FB} - 2\phi_{Fn} + \frac{K_s\epsilon_o q N_D}{C_o^2}\left[1 - \sqrt{1 - \frac{2C_o^2 (V_G - V_{FB})}{K_s\epsilon_o q N_D}} \right]$
Turn-on voltage	$V_T = V_{FB} + 2\phi_{Fp} + \frac{\sqrt{2K_s\epsilon_o q N_A (2\phi_{Fp})}}{C_o}$	$V_T = V_{FB} + 2\phi_{Fn} + \frac{\sqrt{2K_s\epsilon_o q N_D \lvert 2\phi_{Fn}\rvert}}{C_o}$
Conductance (linear area)	$g = \frac{Z}{L}\mu_n C_o (V_G - V_T)$	$g = \frac{Z}{L}\mu_D C_o (V_G - V_T)$
Mutual conductance	$gm = \frac{Z}{L}\mu_n C_o V_D$ When $V_D \leq V_{Dsat}$	$gm = \frac{Z}{L}\mu_p C_o V_D$ When $\lvert V_D\rvert \leq \lvert V_{Dsat}\rvert$
Max. frequency	$f_o = \frac{g_m}{C_G} \leq \frac{\mu_n V_D}{L^2}$ When $V_D \leq V_{Dsat}$	$f_o = \frac{g_m}{C_G} \cdot \leq \frac{\mu_p \lvert V_D\rvert}{L^2}$ When $\lvert V_D\rvert \leq \lvert V_{Dsat}\rvert$
Series resistance effect	Linear area $g(obs) = \frac{g}{1 + (R_s + R_d)g}$ Saturated area $g_{msat}(obs) = \frac{g_{msat}}{1 + R_s g_{msat}}$	

(After Textbook of Grove)

10. High-K Materials

Material	κ	E_g [eV]	ΔE_c [eV]	Stable on Si	Crystal structure
SiO_2	3.9	9	3.1	Yes	Amorphous
Si_3N_4	7.8	5.3	2.4	Yes	Amorphous
Y_2O_3	15	6	2.3	Yes	Cubic
La_2O_3	30	6	2.3	Yes	Hexagonal, cubic
Pr_2O_3	31			Yes	
Dy_2O_3	14	4.8		Yes	
Ta_2O_5	26	4.4	0.3	No	Orthorhombic
TiO_2	80	3.05	0.05	No	Tetragonal
HfO_2	25	~6	1.5	Yes	Monoclinic, tetragonal, cubic
ZrO_2	25	5.8	1.4	Yes	Monoclinic, tetragonal, cubic
$HfSi_xO_y$	~10	~6	1.5	Yes	Amorphous
$ZrSi_xO_y$	~10	~6.5	1.5	Yes	Amorphous
Al_2O_3	9	8.8	2.8	Yes	Amorphous

FIN !

Renesas Design Vietnam Co., Ltd.