Modeling Bipolar Power Semiconductor Devices

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Modeling Bipolar Power Semiconductor Devices

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SYNTHESIS LECTURES ON POWER ELECTRONICS #5

ABSTRACT

This book presents physics-based models of bipolar power semiconductor devices and their implementation in MATLAB and Simulink. The devices are subdivided into different regions, and the operation in each region, along with the interactions at the interfaces which are analyzed using basic semiconductor physics equations that govern their behavior. The Fourier series solution is used to solve the ambipolar diffusion equation in the lightly doped drift region of the devices. In addition to the external electrical characteristics, internal physical and electrical information, such as the junction voltages and the carrier distribution in different regions of the device, can be obtained using the models.

KEYWORDS

power semiconductor devices, physics-based model, Fourier series solution, drift region, carrier diffusion, transient switching behavior

We dedicate this book to our families, particularly Sheryl, Carol, and Anna, who support our endeavors.

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Preface

This book is a culmination of collaborative efforts that span more than a decade. Many students at three universities, the University of South Carolina-Columbia, Cambridge University, and the University of Nebraska-Lincoln, have contributed to the body of knowledge developed on the topic of modeling power devices. It is hoped that the reader will be able to take the framework presented here to utilize simulation models relevant to their particular need and adapt them to new changes in device design and semiconductor material systems. The exposition of the semiconductor properties and device operation with their governing equations is relevant for many areas of study in electronics. The specifics of implementation for simulation are also generally relevant for device descriptions tied to circuit simulators or systems designs. The level of knowledge required to readily use this book is a basic understanding of semiconductor physics with power semiconductor device structure desirable, but not necessary.

Tanya K. Gachovska, Jerry L. Hudgins, Enrico Santi, Angus Bryant, and Patrick R. Palmer
February 2013

Nomenclature

A	Active device area, cm^2
a	Current fall slope , As^{-1}
A_i, b_i, and m_i	Amplitude parameter (cm^{-1}), ionization energy parameter (Vcm^{-1}), and fit parameter
a_i	Ratio of intercell area to the total die area
b	Ratio of electron and hole mobilities
V_{BD}	Breakdown voltage, kV
C_{CG} and C_{GE} and C_{dep}	Miller and gate emitter capacitance, μF
C_{CE} and C_{dep}	Collector emitter and depletion capacitance, μF
C_n and C_p	Auger coefficients, cm^6/s
C_J	Junction capacitance, μF
C_{J1} and C_{J2}	Junction capacitance at junction J_1 and J_2, μF
C_{oes}	Output capacitance provided in an IGBT data sheets μF
C_{OX}	Oxide capacitance, μF
C_{ox}	Oxide capacitance per unit area, μFcm^2
C_{res}	Reverse transfer capacitance of a IGBT, μF
C_{sn}	Snubber capacitance, μF
d_1, W, and d_2	Depletion region thicknesses of each section of $N^+N^-P^+$ regions, respectively, cm
D	Ambipolar diffusivity, cm^2s^{-1}
D_{diff}	Diffusivity constant, cm^2s^{-1}
D_n and D_p	Electron and hole diffusivities, cm^2s^{-1}
D_{n_P} *and* $D_{p_{N+}}$	Minority carrier diffusivities in P and N^+ region, cm^2s^{-1}
D_{pN}	Minority carrier diffusivities in N buffer layer, cm^2s^{-1}

D_{N^-}	Electron diffusivity in N^- region, cm^2s^{-1}
E_G	Band gap energy, eV
G	Generation rate, cm^3/s
$G(s)$	Transfer function
I_A i_{sn} and i_L	Diode, snubber, and load currents, A
I_F	DC forward current, A
h_n and h_p	Recombination parameters, $cm^{-4}s^{-1}$
I_B, I_C, I_E, and IG	Base , collector, emitter, and gate currents, A
i_C	Collector current, A
I_{CG}	Current due to Miller capacitance, A
I_{even} and I_{odd}	Currents for even and odd numbers of harmonic k, A
I_D	Diode currents, A
i_g	Gate currents, A
I_{mos}	Channel MOSFET current, A
I_{QN}	Capacitive current due to the variation in the charge stored in the buffer region, A
I_n and I_p	Electron and hole currents, A
I_{n0}, I_{n1}, and I_{n2}	Electron current at junctions J_0, J_1, and J_2, A
I_{p0}, I_{p1}, and I_{p2}	Hole current at junctions J_0, J_1, and J_2, A
I_{disp}, I_{disp1}, and I_{disp2}	Displacement currents, A
i_{sn}	Snubber currents, A
J	Maximum current density, Acm^{-2}
J_0, J_1, and J_2,	Junctions 0, 1, and 2
J, J_p, and J_n	Total, hole, and electron current densities, Acm^{-2}
$J_{p\|drift}$ and $J_{p\|diff}$	Hole drift and diffusion current densities, Acm^{-2}
$J_{n\|drift}$ and $J_{n\|diff}$	Electron drift and diffusion current densities, Acm^{-2}
$J_{n(PN^-}$ and $J_{P(N^+N^-)}$	Electron carrier densities at the PN^- and N^+N^-junctions, Acm^{-2}
k and n	Harmonic indexes for CSR carrier density of Fourier series representation

k	Boltzmann's constant (1.381×10^{-23} J/K)
K	Coefficient
K_{FV}	Feedback constant
K_p	Transconductance, AV^{-2}
L_{ch} and W_{ch}	Channel length (cm) and width (cm) of the MOS structure
l_m and l_1	Intercell half-width and the width due to voltage V_{GE}, cm
L_{pN}	Diffusion lenth in N buffer layer, cm^2s^{-1}
L_S	Stray inductance, H
M	Number of the terms of the Fourier series
n_{B0} and n_{B1}	Electron doping concentration in the P-base at the junction J_0 and J_1, cm^{-3}
N_{D2}, N_{D1}, N_A	Doping concentration in the $N^+N^-P^+$ regions, respectively, cm^{-3}
N_{N^-}	Doping concentration in the N^- region, cm^{-3}
N_{SC}	Space charge density, cm^{-3}
n	Electron carrier concentration, cm^{-3}
n_i	Intrinsic carrier concentration, cm^{-3}
$n_0 \ldots n_7$	Nodes in lumped-charge model
N	Buffer layer
N^- and N^+	Lightly doped and heavy doped hole regions
N_{N^+}, N_P, and N_N	Doping concentrations in N^+ and P region, and the buffer layer cm^{-3}
N_{N^-} and NH	Doping concentrations of the N^- drift region and buffer layer, cm^{-3}
N_A	Acceptor doping concentration, cm^{-3}
N_D	Donor doping concentration, cm^{-3}
p	Hole carrier concentration, cm^{-3}
P and P^+	Base and heavy doped hole regions
P_B	Doping concentration in base region, cm^{-3}
p_{N0} and p_{NW}	Hole concentrations at the two ends of the buffer layer, cm^{-3}
p_{N^-0}	Concentration in the beginning of the N^- drift region, cm^{-3}

$p(x)$	Ambipolar carrier density as a function of position, cm^{-3}
$p(x; t)$	Ambipolar carrier density as a function of position and time, cm^{-3}
$p_0(t)$	DC Fourier series component of the carrier storage region (CSR) carrier density profile, cm^{-3}
$p_k(t), p_n(t)$	k^{-th} - or n^{-th} Fourier series component of CSR carrier density profile, cm^{-3}
p_{x1} and p_{x2}	Excess carrier concentrations at the two boundaries of the drift region, cm^{-3}
p_{T1}, p_{T2}, and p_T	Carrier densities of the two points of a segment and the carrier density of the segment, cm^{-3}
p_{T_k}	Carrier densities of the kth segment, cm^{-3}
q	Unit electrical charge ($\simeq 1.6 \times 10^{-19}$C)
Q_B	Total electron charge in the base, C
Q_N	Charge stored in the buffer region, C
Q_{RR}, I_{RM}, and T_{RR}	Reverse recovery charge (C), reverse recovery peak current (A) and reverse recovery time (s)
R	Recombination rate, cm^3/s
R_g and L_g	Resistance (Ω) and inductance (H) in the gate circuit
R_L and L_L	Load resistance (Ω) and inductance (H)
R_{SRH}	Shotkley-Read-Hall carrier recombination rate, $cm^{-3}s^{-1}$
R_{sn}	Snubber resistance, Ω
$\tilde{p}_x$ and $\tilde{p}_k$	Carrier density profile in space and time domain
S	Softness factor
T	Absolute temperature, K
T_0	Time at which the diode current become equal to zero, s
T_1	Time at which the peak reverse current I_{RM} occurs, s
T_A	Difference between T_1 and T_0, s
V_{AK}	Voltage drop across the power diode, V
V_{appl}	Voltage applied to $P^+N^-N^+$ structure, V

V_{BR}	Breakdown voltage, V
V_{BE}	Base emitter voltage, V
V_{CE}	Collector emitter voltage, V
V_{DC}	DC voltage supplied to the circuit, V
V_d	Depletion layer voltage, V
V_{d1} and V_{d2}	Depletion layer voltages, V
V_{GE}	Gate emitter voltage, V
V_{GS}	Gate source voltage, V
V_{L_s}	Stray inductance (L_s) voltage, V
V_{N^-}	Drift region voltage drop, V
V_{j0}, V_{j1}, and V_{j2}	Voltage drop at junctions J_0, J_1, and J_2, V
v_{sat}	Saturation velocity, cm s^{-1}
V_{seg}	Voltage drop of a segment, V
V_T	Thermal voltage, V
V_{TH}	Threshold voltage, V
W_B	Base width, cm
W_d	Widths of the depletion region, cm
W_1 and W_2	depletion widths, cm
W_{N^-} and WH	Widths of the depletion region on the N^- and buffer layer, cm
W_{d1} and W_{d2}	Depletion widths, cm
x_1 and x_2	Boundary positions of the carrier storage region, cm
α_i and α_{eff}	General ionization coefficient, effective ionization coefficient, cm^{-1}
Δx	Segment thickness, cm
E	Electric field strength, V/cm
ϵ	Material permittivity, Fcm^{-1}
μ_n and μ_p	Electron and hole mobilities, ($cm^2V^{-1}s^{-1}$)
τ_B	High-level lifetime in the P- base region, s
τ_H	Carrier lifetime in N buffer-layer, s

τ_{lim}	Time constant, s
τ_n and τ_p	Electron and hole lifetimes, s
τ_{HL} and τ	High-level injection lifetimes, s
τ_{N^-}	Electron lifetime in N^- region, s
τ_{n_P} *and* $\tau_{p_{N^+}}$	Electron and hole lifetimes in P and N^+ region, s
τ_{pN}	Minority carrier lifetime in N buffer layer, cm^2s^{-1}
τ_{rr}	Reverse recovery time constant, s
AC	Alternating current
ADE	Ambipolar diffusion equation
BJT	Bipolar junction transistor
CSR	Carrier storage region
DC	Direct current
IGBT	Insulated gate bipolar transistor
MOS	Metal-oxide-semiconductor
MOSFET	Metal-oxide-semiconductor field-effect transistor
PT	Punch-through
Si	Silicon
SRH	Shockley-Read-Hall